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ICE PROPELLER INTERACTION FORCES

VOLUME I

Prepared for:
Transportation Development Centre
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April 1990

by

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Un sommaire en français de ce rapport est inclus avant la Table des matières.

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16. Abstract

This project has systematically evaluated the influence of many parameters on the ice loading of propulsion systems. This is done by the use of model test series in an ice model basin. Both Open and Ducted propellers were studied.

The influence of the ice thickness, ice strength, ice block size, amount of ice fed to propeller, propeller revolutions, propeller pitch and vessel speed were established.

Separation of components of ice load was introduced. The three components are: basic hydrodynamic load in the absence of ice, ice-induced hydrodynamic load (or change of basic hydrodynamic load due to the presence of ice) and direct ice contact load.

Model test results were correlated with full-scale data of Jarvsaar and Robert Lemeur.

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16. Résumé

Le présent projet avait pour but d'évaluer de façon méthodique l'influence de divers paramètres sur la sollicitation des systèmes de propulsion dans les glaces. Cette évaluation s'est faite au moyen d'essais sur modèles réduits d'hélices protégées par une tuyère et d'hélices non protégées.

Les essais ont permis de déterminer l'importance des facteurs suivants : épaisseur et résistance de la glace, dimensions du bloc, quantité de glace en contact avec l'hélice, pas de l'hélice, régime du système propulsif et vitesse d'avancement dans la glace.

Trois composantes de la charge globale exercée par les glaces ont été définies, soit : la charge hydrodynamique en l'absence de glace, la charge hydrodynamique en présence de glace et la charge directe au contact de la glace.

Les résultats des essais sur modèles réduits ont été comparés à ceux d'essais en mer avec les navires Jarvsaar et Robert-Lemeur.

Des équations de prévision de la performance de systèmes de propulsion ont été mises au point pour une plage donnée de paramètres de conception de systèmes propulsifs, de caractéristiques mécaniques des glaces et de conditions d'exploitation.

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SUMMARY

This project incorporated the first extensive model test series for systematic evaluation of the influence of many parameters on the ice loading of propulsion systems. Using a custom-built test apparatus and novel testing techniques, the project studied both open and ducted propellers, and addressed the influence upon ice loading of ice thickness, ice block size, the amount of ice entering the propulsion system, ice strength, propeller pitch, propeller revolutions and vessel speed.

A primary objective was to obtain a basic understanding of the nature and magnitude of the mechanisms which contribute to the loads on propulsion systems in the presence of ice. This is essential for the accurate prediction of ice loading and subsequently the development of rational criteria for machinery protection regulation of icegoing vessels.

The ice-induced propulsion loads were separated into two key components. The first was the indirect ice load or ice-induced hydrodynamic load, and the second was the direct contact ice load. Data analysis established that both of these components are of important magnitude. Moreover, the parametric dependencies of the two components are different and follow individually clear and logical trends. The key parameters influencing the indirect ice load are propeller size, propeller revolutions and ice thickness. The corresponding key parameters for the direct ice load are ice thickness, ice strength and propeller diameter.

Correlation between ship and model propeller ice loading was investigated by comparing the full scale trials data for two vessels with predictions based directly on the model test analysis. The first vessel, Jarvsaar, is an ice going trawler, equipped with a single CP propeller, which was tested both with and without a duct. The second, the arctic supply vessel Robert Lemeur, has twin ducted CP propellers.

The Jarvsaar propulsion system measurements were supported by both underwater video records of propeller and ice interaction and good environmental data (ice properties). It was therefore possible to make direct comparisons between propulsion loads from model and ship for similar ice interaction events. A good correlation of close to unity was established between model predictions and full scale measurements for both the open and ducted propeller cases. In the case of the Robert Lemeur data, ship and model correlation was difficult to establish meaningfully, since direct visual records of propeller and ice interaction were not taken and environmental data coverage was inadequate. Consequently the Robert Lemeur data were not used to establish correlation factors.

SOMMAIRE

Ce rapport concerne la première batterie complète d'essais sur modèles réduits visant à évaluer de façon méthodique l'influence de divers facteurs sur la sollicitation des systèmes de propulsion dans les glaces, et notamment l'épaisseur de la glace, les dimensions du bloc, la quantité de glace envahissant le système propulsif, la résistance de la glace, le pas de l'hélice, le régime du système propulsif et la vitesse d'avancement dans la glace. Les essais ont porté sur des hélices tantôt protégées par une tuyère, tantôt non protégées, et mettaient en oeuvre un montage spécialement conçu et des procédés nouveaux.

Un des principaux objectifs visés était de déterminer la nature et l'amplitude des formes d'interaction glaces-pales d'hélice, facteurs essentiels pour la prévision exacte des charges de glace et, par conséquent, pour la formulation de la réglementation visant la sécurité de la navigation en eaux chargées de glaces.

Aux fins de la présente étude, la charge globale exercée par les glaces a été divisée en deux composantes majeures, c'est-à-dire la charge directe provenant du contact glaces-hélices et la charge indirecte, ou hydrodynamique. L'analyse des données a révélé non seulement que ces deux composantes sont importantes, mais qu'elles évoluent indépendamment l'une de l'autre en fonction de paramètres différents et suivant une courbe bien définie. Ainsi, la charge indirecte varie principalement en fonction de la dimension et du régime du système propulsif et de l'épaisseur de la glace, alors que la charge directe est surtout influencée par l'épaisseur et la résistance de la glace et le diamètre de l'hélice.

Les résultats des essais en mer de deux navires ont été comparés aux résultats théoriques obtenus à partir d'essais sur modèles réduits, afin de déterminer la corrélation entre les charges observées en conditions réelles et celles obtenues en bassin. Les navires en question sont le chalutier Jarvsaar, équipé d'une seule hélice à pas constant, et qui a été essayé tantôt avec une tuyère, tantôt sans protection de l'hélice, et le ravitailleur Robert-Lemeur, équipé de deux hélices à pas constant avec tuyères.

La mesure des charges exercées par les glaces sur le système propulsif du Jarvsaar a été complétée par un enregistrement des interactions de l'hélice avec les glaces au moyen d'une caméra sous-marine et par des données environnementales appropriées (caractéristiques mécaniques de la glace). Il a donc été possible d'établir, pour des conditions glacielles données, une comparaison directe entre les charges observées en conditions réelles et celles observées lors des essais sur modèle réduit. Les résultats théoriques obtenus à partir des essais sur modèle réduit se sont avérés presque conformes aux valeurs enregistrées en conditions réelles, et ce aussi bien lorsque l'hélice était protégée par une tuyère que lorsqu'elle ne l'était pas. Dans le cas du ravitailleur Robert-Lemeur, il a été plus difficile d'établir la corrélation entre les deux séries de résultats, puisque les interactions hélices-glaces n'ont pas été enregistrées par caméra et que les données environnementales étaient insuffisantes. Par conséquent, les données recueillies relativement à ce navire n'ont pas été retenues pour la détermination des facteurs de similitude recherchés.

La présente étude a permis d'établir que le montage spécialement conçu pour les essais sur modèles réduits et les techniques de modélisation utilisées sont valables, puisqu'ils permettent de simuler assez exactement l'interaction hélices-glaces réelle.

Les équations de prévision de l'influence de la charge des glaces sur la poussée et le couple moteur d'hélices avec ou sans tuyère ont été établies en tenant compte du type d'interaction entre l'hélice et les glaces, des caractéristiques mécaniques des glaces et des paramètres de fonctionnement des systèmes propulsifs. Il a été constaté qu'une hélice sans tuyère est généralement exposée à des charges plus élevées qu'une hélice avec tuyère; l'hélice à tuyère est plus sensible aux niveaux élevés d'interaction avec les glaces, la charge glacielle résultante approchant celle que subit une hélice sans tuyère. Les chercheurs sont d'avis que les modèles de prévision issus des présents travaux conviennent à l'évaluation qualitative d'un système de propulsion donné, mais qu'ils doivent, pour servir au calcul des charges glacielles à prendre en compte lors de la conception des systèmes de propulsion, être complétés par des algorithmes permettant de préciser les interactions hélices-glaces selon les caractéristiques de conception du navire et son profil d'exploitation.

1. INTRODUCTION

The issue of ice loading on open versus ducted propellers has been an item of discussion and some differences of opinion for the past several years. There has been a clear lack of comparative facts whereby these two systems could be compared objectively in terms of ice loading as well as efficiency of operation.

This project marks a major step towards developing the knowledge of the phenomena governing the ice loading on these propulsion systems. It uses model tests to perform systematic variation of the key parameters considered to influence ice loading. It also employs full scale data from two of the most tested ships for propeller ice loading at the time of initiation of this project. These are Robert Lemeur and Jarvsaar. The full scale data are used to calibrate the information gained from the model basin. Subsequently a rational methodology for design load determination for propulsion systems in ice is developed.

Propulsion loading was found from the Robert Lemeur full scale measurements to be surprisingly high when the nozzle was clogged with ice without actual milling of ice occurring. It thus became important to establish the influence of ice on the hydrodynamic loading of the propeller in a nozzle. This raised the important question, fundamental to the initiation of this project, of how to deal with the anticipated differences in scaling between the hydrodynamic influences of ice and those forces resulting from direct ice impact.

The understanding of the mechanisms of propulsion ice interaction is approached using a series of customized, novel model techniques, which allows propeller loading to be separated into three components, a pure hydrodynamic load, an ice induced hydrodynamic load and a direct ice load. This is very important when, for example, using ice model tests to establish estimates for full scale loads. The hydrodynamic component of the ice-induced load is not ice strength dependent whereas the direct ice load clearly is. Thus the prediction of full scale ice loading requires this breakdown in order to achieve correct scaling and an accurate estimate.

This breakdown of the ice-induced load is performed for both the ducted and open propellers. The ice-induced hydrodynamic load has been considered to be potentially very important for the ducted propeller, causing long duration, high amplitude, vibratory loading. In the case of the open propeller, this issue has not formerly been raised in a similar manner. However, it was considered important to follow the similar approach in order to investigate this potential difference between the open and the ducted propeller.

The report is divided into 4 technical Chapters. Chapter 2 introduces the full scale data that are used for the purpose of comparison and scaling of model test data. These full scale data are also used to identify those actual extreme loading situations to be used for determining design loads.

Chapter 3 introduces the model tests, the model test data and their analysis, which is described in detail in APPENDIX A.

Chapter 4 provides comparisons between model and full scale data in order to establish the degree to which model tests scale to full scale values of loading.

Chapter 5 describes the development of formulae for predicting the propeller and ice interaction loads and describes how these would eventually be used in establishing design loads for specific vessel designs.

In Chapter 6, the conclusions and discussion of the results are given.

Finally, Chapter 7 gives recommendations for the use of the results and also for areas of least knowledge related to propulsion ice loading which should be resolved next.

2. FULL SCALE DATA

2.1. General

The Jarvsaar tests are the only ones available to this project where the same ship has been tested with both an open and a ducted propeller. The data have been reported as confidential in (1 - 4). This project has access to that project where the loads on the propulsion systems of Robert Lemeur and Jarvsaar have been compared (4). The data are not reinterpreted here, but taken directly from the previous reports.

Events from the Jarvsaar report are selected for two purposes. First, there has been an unknown amount of influence upon the measured loads due to the dynamic response of the propulsion system to the ice input load. Thus it had been concluded that the load that was inferred directly as a response of the shaft thrust and torque was not necessarily representative of the actual load at the propeller. The selection of Jarvsaar data in section 2.2.1 is therefore based on both the requirement of the design load calibration as well as to resolve the influence of dynamics on the propulsion train response. The interpretation of the dynamics is given in (9) and summarized in Section 2.2.2.

The data for the propeller loading of Robert Lemeur has been selected on the same basis as that for the Jarvsaar. Robert Lemeur data selection and data interpretation is given in (5) and used in Section 2.3.1 and Section 2.3.2 respectively.

2.2. Jarvsaar

2.2.1. Selection of data

The main criteria for data selection was to determine the actual load that had caused the highest measured loads on trials. In the case of Jarvsaar, there were limited data to choose from and the choice was obvious in most cases. The highest event of its kind was selected. In the case of thrust, the model tests were limited to a medium to high pitch, whereas the full scale tests had the highest thrust events at low pitch. These were often associated with backing and/or with high rudder angles. These conditions are to be recognized as important ones for design purposes and have therefore been selected for the purposes of model and full scale comparison. Additional events were selected beyond the maximum ones due to a lack of conformity between the parameters for the highest events and the model test parameter range. Highest events in the categories which matched the model test parameter range were subsequently selected as well.

For the ducted propeller, the events selected from the Jarvsaar data are given below.(numbers of events refer to numbers in (3,4):

6. Blockage event with high amplitude variation of torque response. P/D = 1.3, 1m/s. This represents the highest blockage load event from the tests, and thus gives the ice induced hydrodynamic load for such an event.

9. Highest torque. P/D = -1.12, v = -1.6m/s, a milling event. This is the highest observed milling type load event. It is considered to be a single ice block event and thus comparable to a model test event from the model tests.

11. Highest thrust. P/D = -0.45, v = -1.5 m/s, a blockage event . The highest load events in terms of thrust have been in conditions outside the parameter range of the model tests. This highest event also had a rudder angle of 29 degrees.

127. The event with the highest thrust in the ahead mode with zero rudder angle and high pitch, P/D = 0.9, v = 2.0 m/s.

For the open propeller, a similar selection excludes the blockage. The event list is as follows:

14. Highest torque. P/D = 0.65, v = 2.1 m/s, a milling event. This is directly comparable to a model test event in ice conditions which simulate the full scale tests.

16. Highest negative thrust, P/D = -0.72, v = -2.7 m/s, resulting from impact of an ice block with the propeller blade. The highest thrust events, in a similar manner as for the nozzle propeller, occured on full scale at conditions outside the model tests parameter range. This particular event occured during backing. This highest load is to be proportionately compared with the model test data in order to arrive at a "design load" condition.

17. Highest positive thrust, P/D = 0.05, v = -2.4 m/s, due to impact between an ice block and a blade. The highest thrust events occured at very low pitch, which again was not covered by the model tests. In order to arrive at "design load" levels, this event is used to determine a multiplier for the model test events with high thrust.

7. Highest thrust peaks (several peaks of similar magnitude), in continuous transit. P/D = 0.85, v = 1.7 m/s.

2.2.2. Interpretation of Data

It is recognized that the measured response of the propeller shaft is not the measurement of the input load. The dynamic behavior of the whole propulsion line influences the amplification/dampening of the input load which is then seen as the response at the shaft.

For the purpose of interpreting back from the shaft thrust and torque response to the input load on the propeller blade, a simulation of the propulsion train of Jarvsaar was undertaken. This is as reported in APPENDIX B. The simulation modeled the components of the propulsion system with their masses, inertial properties, support stiffnesses and material properties.

The results from the simulation led to a best estimate for the actual input load at the propeller and assessment of the dynamic factors of the loading. These are summarized for the selected events in Table 2.1. One main result from the analysis was that there are no dynamic influences on the interpretation of the thrust signal, at least not when the shaft thrust remains completely positive or negative during an event. The simulation model that was used was not capable of interpreting the influence of thrust block clearance and the behavior around zero thrust. The dynamic dampening of the torque load from the propeller to the shaftline where the measurement took place was, however, very large indeed. The analysis suggested that the input torque loading had been of the order of twice the magnitude that was indicated by direct interpretation of the shaft response.

2.3. Robert Lemeur

2.3.1. Selection of Data

The criteria for selecting data from the full scale data set is similar to that for the Jarvsaar. The target is to arrive at "design load" levels starting from the model test results and going through the assessment of similarities of model and full scale conditions . Finally correlation factors between the full scale and model tests results are determined.

For the ducted propeller of the Robert Lemeur, the data selected as being most representative of severe loading conditions have been:

1. Highest torque event (# 117). Ahead, with P/D = 0.9, speed 2.2 m/s, rudder angle 19°. The vessel is progressing in level ice ahead. This is the highest single torque event of its kind. It is not known what the exact ice interaction was, but it is categorized as chopping based on extensive data interpretation.

2. Highest thrust event ahead (# 130). P/D = 0.66, ship speed 2.2 m/s and rudder angle of 7 degrees. The ship has been ramming ridges but it is not known what the exact ice event was. Interaction is called blockage but there seems also to be some direct ice interaction.

2.3.2. Interpretation of Data

The dynamics of these data have been interpreted according to Table 2.1. Here the dynamic analysis has been performed using the same program (5) as for Jarvsaar (9). The main result from this analysis is that there has been even more dampening of the input load between the propeller to the shaft measurement point. This includes a dynamic influence on the thrust load, contrary to the Jarvsaar experience.

Table 2.1. Dynamic Magnification Factors for Full Scale Data, Jarvsaar, Robert Lemeur (8).

DYNAMIC MAGNIFICATION FACTORS FOR JARVSAAR TESTS

TEST	TORQUE (KNM)			THRUST (KN)		
NR	SHAFT	PROP	DMFQ	SHAFT	PROP	DMFT
6	13	24	0.54			
9	32	70	0.46			
11				-100	-100	1.00
14	50	120	0.42	-145	-140	1.04
16				290	280	1.04
17	28	80	0.35	-400	-410	0.98
MEAN DMF			0.44			1.01
SINGLE IMPACT	36	100	0.36			

TABLE

DYNAMIC MAGNIFICATION FACTORS FOR LEMEUR TESTS

TEST	TORQUE (KNM)			THRUST (KN)		
NR	SHAFT	PROP	DMFQ	SHAFT	PROP	DMFT
165	80	400	0.20	720	500	1.44
295	140	360	0.39			
MEAN DMF			0.29			1.44

3.0. MODEL TEST DATA

3.1. Objectives

Provide a full picture of phenomena in propeller ice interaction for open and nozzled propellers.

Provide data to calculate any full scale predictions of propeller ice loads for full scale and model scale comparison.

3.2. General

The test equipment, test program, and detailed analysis of results are reported in APPENDIX A. This main report extracts only those results which are directly required for fulfillment of the objectives of the project. A short description of the tests is also given here, such that the reader can follow the logic behind the model test program and the subsequent use of the model data in the analysis.

The results used for the project objectives are the thrust and torque signals, which accordingly are analyzed in APPENDIX A. The main components of the analysis are presented here.

This Chapter is divided into the following sections:

- Section 3.3. Test Program. This describes the tests in general terms in a summary fashion.
- Section 3.4. Test Results. This gives only those results which are directly used for the development of mathematical models and for establishing the basis for model and full scale comparison of thrust and torque loading.
- Subsection 3.4.1. General. This describes how the results are presented and what the purposes of such presentations are.
- Subsection 3.4.2. Hydrodynamic Load. This gives the variation of the hydrodynamic load without any ice present.
- Subsection 3.4.3. Ice-Induced Hydrodynamic Load. This gives a method for extracting the ice-induced hydrodynamic load from the model test results.
- Subsection 3.4.4. Direct Ice Load. This gives the balance of the total load variation after the hydrodynamic and ice-induced hydrodynamic loads are subtracted.

- Subsection 3.4.5. Comparison of open and ducted propeller total ice loads.

- Section 3.5. Discussion on open and nozzle propeller loads.

3.3. Test Program

3.3.1. Test Equipment

A test vessel was designed from basic principles and tailor made for this project. The equipment was to be as flexible as possible for the purposes of both this project and any future similar applications.

The design is shown in Figure 3.3.1., in a schematic format. Photos of the equipment are shown in Figures 3.3.2. and 3.3.3.

Propeller diameter is 0.28 m, and the range of shaft revolutions matched that which could be covered by the frame frequency of the video camera, which is 30/second, corresponding to a shaft speed of 7.5 RPS. The nozzle is a 37-type nozzle which is commonly used for icebreakers. An existing propeller, originally intended for use on the centre shaft of the Louis S.St.Laurent model, was selected. A drawing of the propeller is shown in Figure 3.3.4. The construction is flat plated and of Kaplan type blade shape. The same propeller was used for both open and ducted propeller applications.

The design values of the equipment fulfill the requirements for typically any model scale from 7 to 30. The smallest propeller thereby modelled is just under 2 meters and the largest is 8.4 meters. All known icebreaker propellers with either nozzles or open propellers are at least 1.9 meters and no more than 6.6 meters in diameter.

The following signals from the propulsion test vessel were recorded:

- shaft thrust
- shaft torque
- shaft bending (horizontal and vertical)
- blade bending
- blade spindle torque
- longitudinal force on nozzle (2, top/bottom)
- RPM

Video equipment used was IMD standard video cameras both above and under water, plus a black and white underwater video. The light used to obtain a clear view of the propeller and ice interaction was stroboscopic. The frequency was matched to the propeller blade frequency at each rate of propeller rotation. Thus it was possible to obtain a frozen picture of the interaction at each blade. The camera setup is schematically shown in Figure 3.3.1.

Data aquisition was performed using the IMD standard system. The data were collected digitally at a frequency of 50 Hz and analogically as a backup onto a tape. Selected data was redigitized at a frequency of 200 Hz, in order to establish the influence of the sampling frequency on the results.

3.3.2. Tests

The following types of test were performed, the purpose of each test type being explained:

1. Hydrodynamic reference tests. These are to establish the basic undisturbed reference loadings of the propulsion system without ice. They are recorded for all parameter combinations used in the ice interaction tests.

2. Blockage tests. These were performed to establish the systematic influence of a plate type blockage at the entrance to the nozzle on the hydrodynamic loading of the ducted propulsion system. These tests were performed at bollard condition only.

3. Premilled tests. This test on the open propeller is similar in nature to the blockage tests on the ducted propeller. A premilled ice block is driven close by the propeller, without touching, in order to establish the influence of the presence of an ice block on the hydrodynamic loading of the propeller. These tests were performed at bollard condition only.

4. Ice block feeding. Pre-cut blocks were fed to the propulsion system in order to establish the direct influence of ice contact on propulsion loading. In the nozzled propeller case, this also gave the indirect influence of ice when actual blockage conditions occurred. These tests were performed at bollard condition and at higher speeds.

5. Level ice tests. Level ice was broken by an inclined surface-piercing plate ahead of the propeller and provided a continuous supply of ice blocks into the propeller. The blocks were approximately similar in size to the individual blocks under the topic of ice block feeding tests. The difference was that a continuous stream of ice block was supplied to the propulsion. These tests gave the influence of more than one block at a time entering the propulsion.

The parameters varied in the tests were, with levels for them given:

- Propeller pitch, 19^o and 30^o
- Propeller revolutions, 3.7, 5.6 and 7.5 RPS
- Nozzle/Open
- Speeds, bollard, 0.2 and 1.0 m/s

- Ice thickness, 50 , 100 and few 200 mm
- Ice block size, 100 * 100, 200 * 200 and 400 * 400 mm
- Ice flexural strength, approximately 15 - 60 kPa

3.4. Test Results

3.4.1. General

The analysis of the test results in this project is directly focused on the ice loading of propulsion systems as it may relate to design loads and design load event definitions.

A large number of tests were performed and a full interpretation of them is far beyond the scope of this project. In this chapter, the key phenomena governing those aspects of propulsion system loading, considered important to the designer, are presented. The results are explained sufficiently to give the reader an understanding of the loading scenarios and how they take place. Thrust and torque loads only are considered. A more thorough presentation of the results is given in APPENDIX A.

The quantitative interpretation of the thrust and torque results from model tests is presented in terms of the influence of ice on the average load as well as on the maximum amplitudes of load variation. The reference in each case is the basic hydrodynamic average and amplitude of variation.

The loads are divided into three components, as illustrated in Figure 3.4.1. This provides a means of relating propeller ice loading back to basic components, each of which might have different relationships with parameter variations and, consequently, different scaling laws applicable to it.

The basic component according to the concept in Figure 3.4.1 is the propulsion load in the absence of ice. This is called the hydrodynamic load, or the basic hydrodynamic load. The second component of the load is the ice induced hydrodynamic load. This is the load caused by the change of the hydrodynamic flow through the propeller due to the presence of ice. The third component is the direct ice load which is due to the physical contact between the ice and the propeller. This is essentially the load to break the ice, and to accelerate it through the propeller.

In addition to the model tests at IMD, which were carried out in normal atmospheric pressure, the tests performed on the influence of cavitation number on the hydrodynamic loading of a ducted propeller are used here to assess how to best interpret the model test results obtained under normal pressure.

Sub-section 3.4.2 reports the basic hydrodynamic load data, which are then used as a reference for the loads induced by ice. These basic hydrodynamic loads are represented by their mean values.

Sub-section 3.4.3. reports the ice-induced change to the hydrodynamic component of the propulsion load. This specifically excludes the direct influence of ice contact with the propeller. It deals with the influence of ice on the hydrodynamic flow into the propeller and the resulting change of hydrodynamic load. The mean and maximum values are presented.

Sub-section 3.4.4. reports the direct load caused by contact between the propeller and ice. It deals with the remainder of the total load once the basic hydrodynamic load as well as ice-induced hydrodynamic load have been subtracted. The mean and maximum values are presented.

Sub-section 3.4.5. presents the total load caused by ice for open and ducted propeller. The comparison is presented between the ice loads for these systems in terms of influence of nozzle on the loading with increasing ice thickness.

3.4.2. Hydrodynamic Load

The definition of hydrodynamic load is:

The load on propulsion at a given speed, RPM and pitch, without any hull or ice influence.

The hydrodynamic torque and thrust loads are given in Figures 3.4.2.and 3.4.3., as the base point at zero ice strength. The average value is shown in each respective case . Figure 3.4.2., shows the torque loading and Figure 3.4.3., the thrust loading for the main case, which is for high pitch, 7.5 RPS, and 0 m/s.

The basic hydrodynamic loads are used in this report as a basis for all component load division.

3.4.3. Ice-Induced Hydrodynamic Load

The definition of ice induced hydrodynamic load is:

The change of hydrodynamic load due to the change in water flow through the propeller in the presence of ice, including this effect as the ice passes through the propeller disc.

This load was measured in three different types of tests:

- basic flat plate blockage tests (nozzle propeller)
- actual blockage with ice blocks (nozzle propeller)
- premilled tests (open propeller)

For the nozzle propeller it was anticipated that the indirect ice-induced load could be simulated by a flat plate blockage in front of the nozzle. This however did not turn out to be the case. The actual types of blockage which took place during the ice interaction tests are presented in Figure 3.4.4. Out of these cases, none of the plate blockage type was seen during actual ice interactions. The most important blockage scenario was caused by type 4 blockage in Figure 3.4.4, since ice blocks flow naturally towards the propeller in this manner.

Conceptually, the difference in results between the plate blockage case and type 4 blockage are shown in Figure 3.4.5. This Figure illustrates clearly how the average influence on loads from the plate blockage is more serious than in the actual blockage situations. The amplitude of variation of load is, however, radically more severe for the actual blockage than for the plate blockage. This is explained in terms of the proximity of the ice blocks to the blade. The very small clearance between the propeller blade and ice blocks in the actual blockage case, results in much larger load impulses than for the plate blockage case where the separation in larger.

Quantitative results in Figure 3.4.6., show that the actual blockage loads can have an amplitude of variation of up to 4 times larger than the corresponding plate blockage.

The analyzed blockage load results are shown in Figures 3.4.2 and 3.4.3., on top of the basic hydrodynamic load at zero ice strength.

For the open propeller, the indirect ice load can be defined in the same manner as for the ducted propeller. In practice, however, the geometry of ice interaction is different in the absence of the nozzle. The heaviest ice loads are considered, from both past and this current experience, to be milling events. In this situation, the ice block surrounds the propeller such that the blades cut into the ice with their tips cutting a sector out of the ice block. The ice loads are at their most severe when the cut depth is at its maximum.

This condition of indirect hydrodynamic influence of ice for open propellers is named "premilling" in this project. This is illustrated in Figure 3.4.7. The premilled test simulates the situation where a pre-cut block of solid material to match the shape of the arc around the propeller is used. Different blocks, representing different propeller disc coverages in terms of cutting depth, or sector are used. The blocks do not touch the blades, but are run as close to the blades as is feasible.

The indirect hydrodynamic loads for the open propeller are treated in a similar fashion as the blockage loads. The only difference is that the premilled tests have to be taken on their face value as representing the indirect hydrodynamic load. There is no experiment in this test series to test the validity of this assumption directly. Based on the results however, the outcome is reasonable and quite similar to the blockage loads in the nozzle propeller case. The indirect load from the premilled tests provides a workable approach to separating the total ice load into components. Moreover, the resulting direct ice loads follow consistent parametric trends. This provides reasonable evidence that the approach is correct.

Figures 3.4.8. and 3.4.9., present, at zero ice strength, the interpreted indirect hydrodynamic torque and thrust loads for open propeller loading. A cut depth of 50 % of the blade length, shown in Figures 3.4.8 and 3.4.9, is representative of a high indirect load.

3.4.4. Direct Ice Load

The direct ice load is the actual contact load between ice and the propeller. This is separated from the basic hydrodynamic load and the indirect ice load for the purposes of correct scaling of the results as well as understanding the composition of propulsion loading due to ice interaction. It is considered that the indirect hydrodynamic load due to the presence of ice is not influenced by the strength of ice (or is influenced only to a minimal degree in comparison to other major influences). The direct ice load, however, is directly proportional to the ice strength and the energy required to break the ice in interaction. The whole concept of the direct ice load as a separate component is not necessarily fully true, but is, in the author's opinion, the most acceptable overall concept at this time.

The direct ice load is determined from the model tests by first subtracting the basic hydrodynamic load and the indirect ice-induced hydrodynamic load (or indirect ice load). The remainder is the direct ice contact load. This is illustrated schematically in Figure 3.4.1 with representative data presentations being given in Figures 3.4.2 and 3.4.3.

3.4.5. Ice Load Predictions

The ice load data, as analysed above, have been used to derive predictions of the maximum ice-induced thrust and torque loads acting on open and ducted propellers with the same propeller design parameters and operating conditions. The results, which show directly the effect of enclosing the propeller in a nozzle, are presented in Figures 3.4.10 to 3.4.13, for both single and multiple ice block interactions. The ice loads include both direct and indirect components. The following comparisons are shown.

- Figure 3.4.10.A/B, Maximum thrust/torque events as a function of ice thickness for the open and ducted propellers. This is for individual blocks with 200 mm square areal size blocks.
- Figure 3.4.11 shows the principle of single block versus a continuous stream of blocks through the propeller.
- Figure 3.4.12.A/B, shows the factor for nozzle and open propeller between the continuous stream of blocks versus single block feeding into the propeller, for the thrust/torque events.
- Figure 3.4.13.A/B, shows the maximum thrust/torque load for a continuous stream of ice blocks through the propeller for open and ducted propeller.

3.5. Discussion

The propeller and ice interaction load component analysis from the model tests provided logical results for both the open and ducted propellers, which are readily explained in simple physical terms. The following are the main results from the model tests:

1. The indirect load is a significant component for both the open and ducted propellers. The most important parameters influencing it are the diameter of the propeller, RPM and ice thickness (less than first two).
2. The most important parameters influencing the direct propulsion ice load are ice thickness, ice strength and propeller diameter. A secondary parameter is block size. Other parameters have minor influence for both the open and ducted propeller. The direct ice load does not appear to depend significantly on some parameters that might have been expected, such as the revolutions of the propeller, speed of the vessel or propeller pitch (within the range of test parameters with a lowest value of 19 degrees).
3. The nozzle propeller maximum ice load for single ice block interaction is lower than the similar load for the open propeller. This difference appears to increase with increasing ice thickness. This result is valid at least up to the thickness of ice in these tests, the maximum being the blade length of the propeller.
4. When feeding a continuous stream of ice blocks through the propeller, the relationship between the open and the ducted propeller changes. They both have close to

similar maximum ice loads for both thrust and torque. The influence of thickness is, however, still bigger for the open propeller than for the ducted propeller. The duct slows down the ice going through the propeller such that there are multiple block interactions and the load increases considerably from the single block situation. In the open propeller case, the blocks are quickly and individually milled and in fact no multiple block interaction was observed.

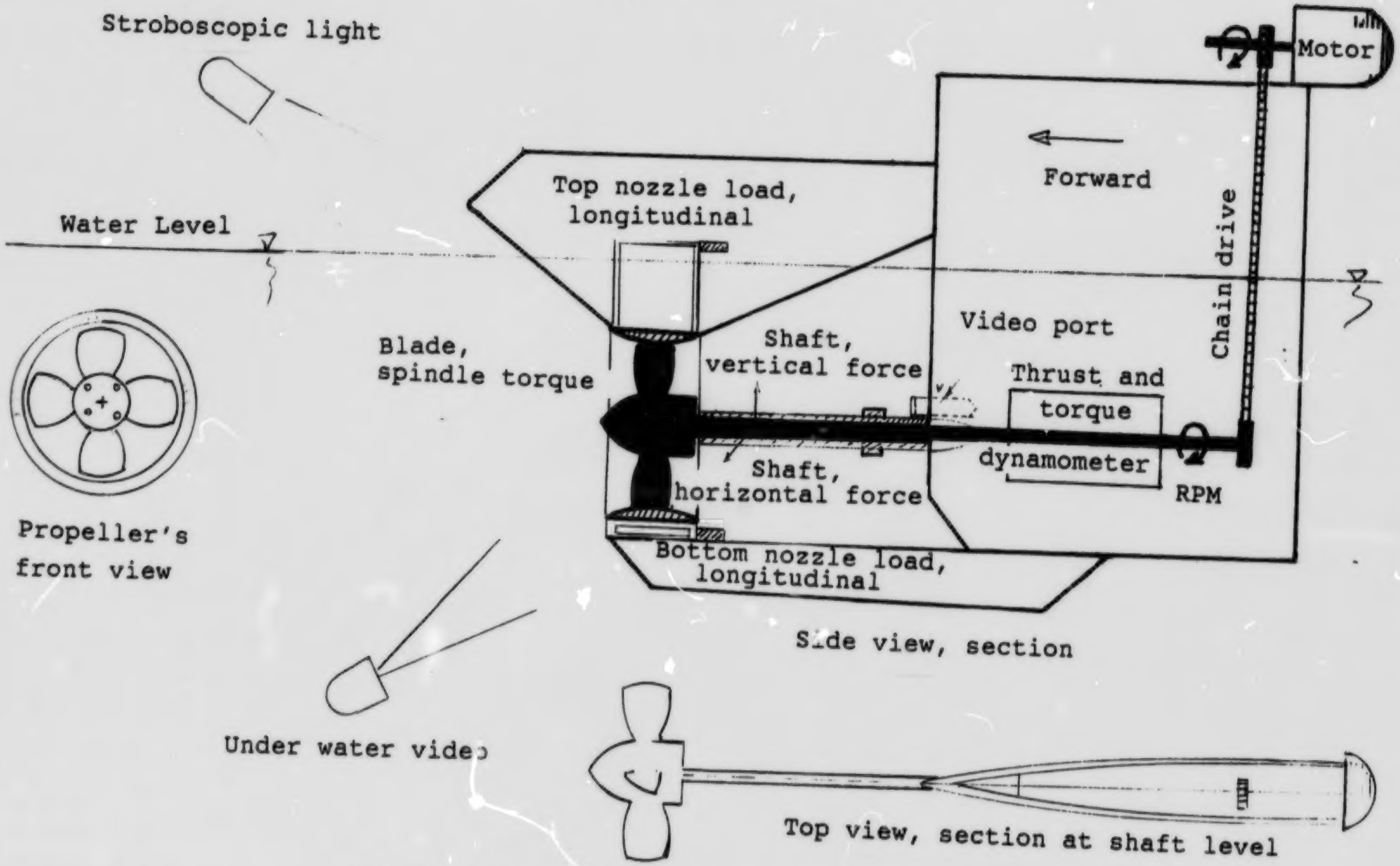


Figure 3.3.1. Schematic presentation of propulsion model test vessel.

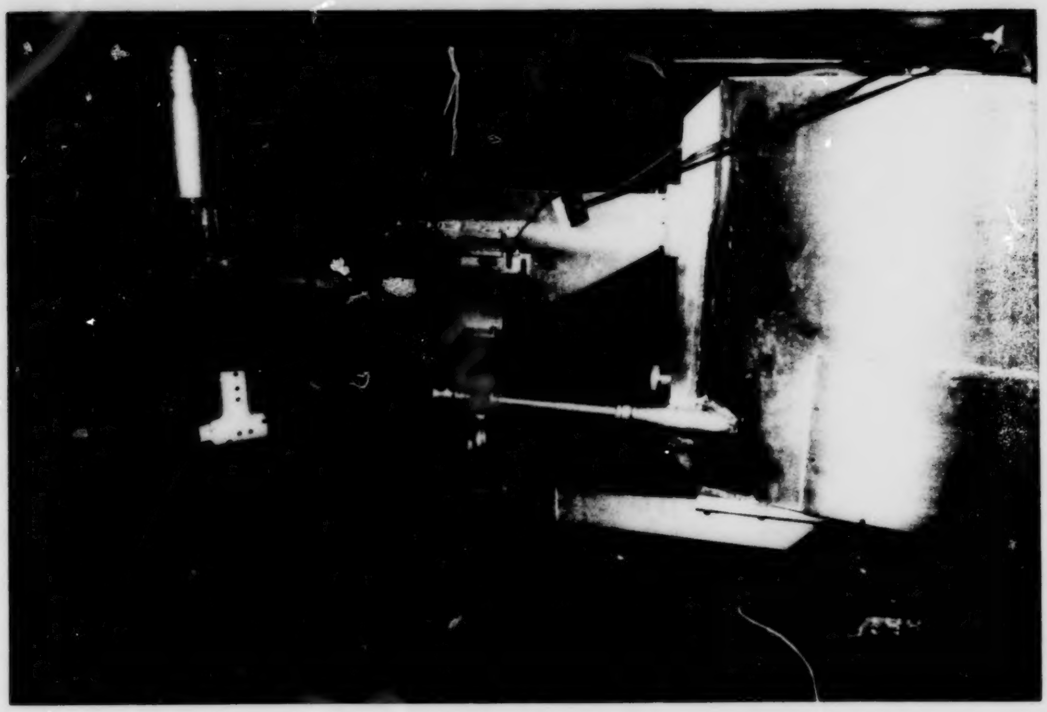


Figure 3.3.2. Test equipment, propulsion model test vessel

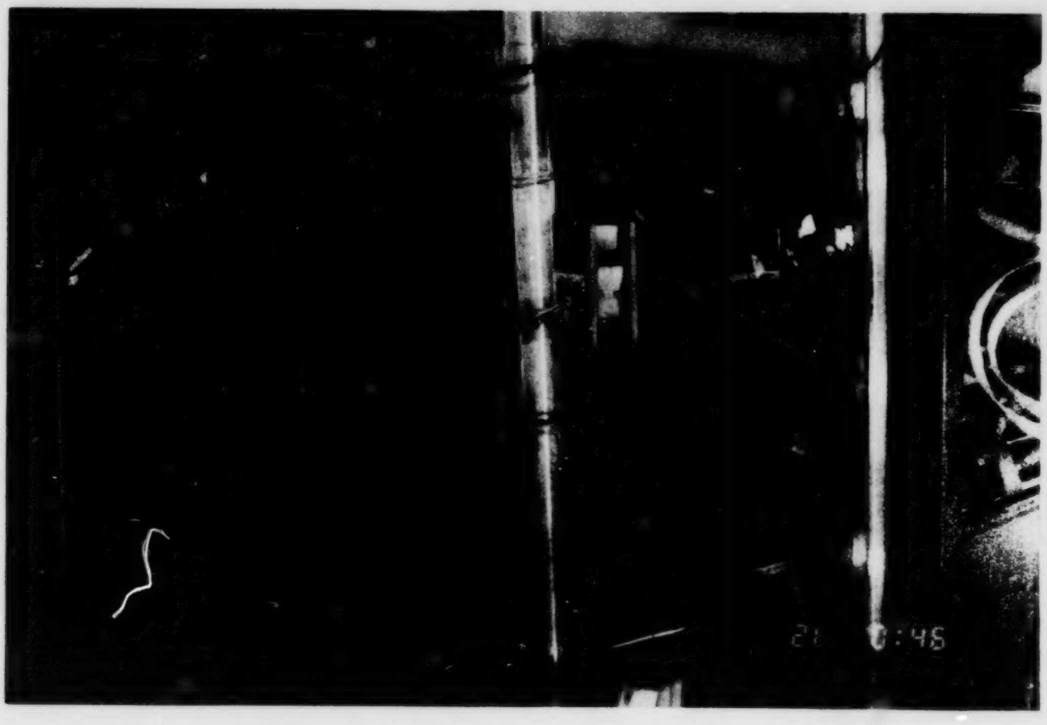
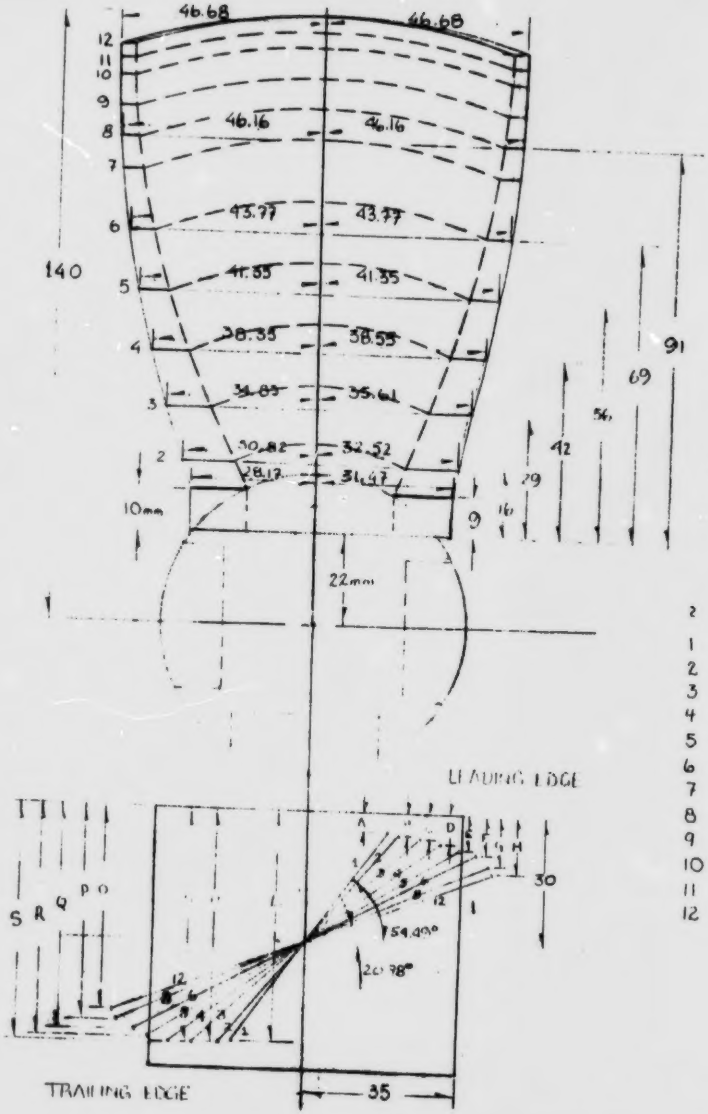


Figure 3.3.3. Test equipment, single block feeding setup.

RIGHT HAND TURNING PROPELLER



LETTER	z	DIMENSION (mm)
A	1	4.28
B	2	5.07
C	3	5.65
D	4	6.69
E	5	7.89
F	6	9.14
G	8	11.18
H	12	13.44
L	1	52.93
M	2	53.37
N	3	53.82
O	4	53.19
P	5	52.11
Q	6	50.86
R	8	48.82
S	12	46.56

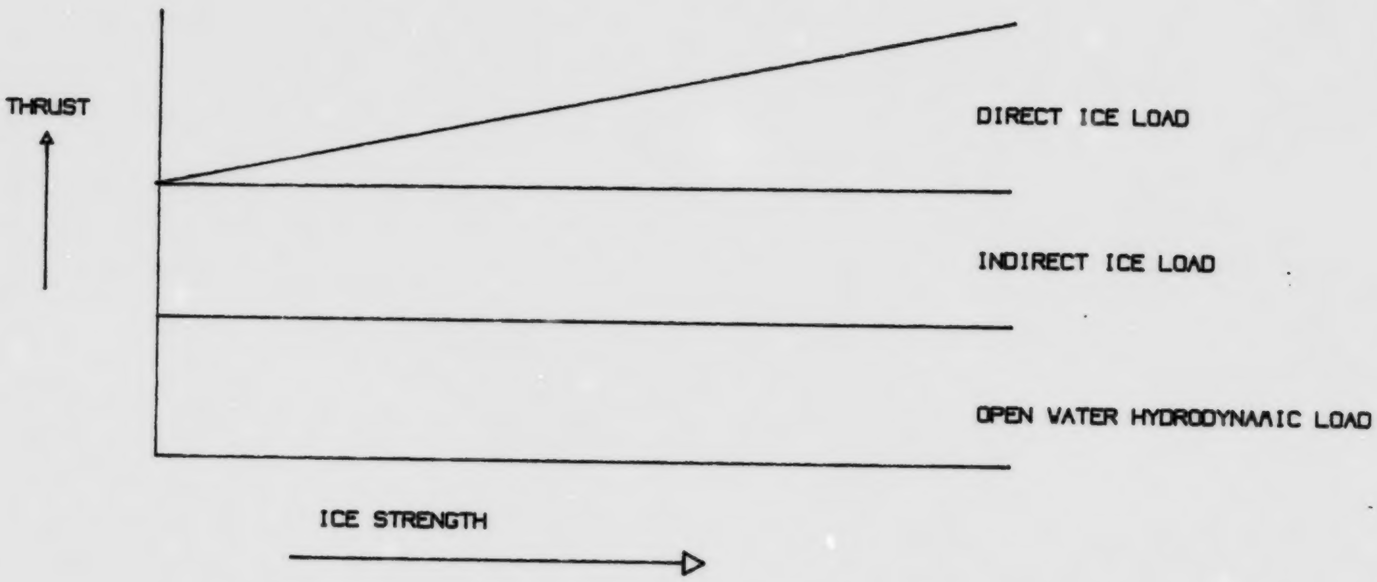
z	RADIUS	ANGLE (θ) (DEG)	TRAIL (z)	LEAD (z)	TRAIL (λ)	LEAD (λ)
1	35	54.49	22.93	25.62	28.17	31.47
2	42	50.18	23.67	24.98	30.82	32.52
3	56	43.15	23.82	24.35	34.83	35.61
4	70	37.20	23.19	23.31	38.35	38.55
5	84	32.32	22.11	22.11	41.35	41.35
6	98	28.47	20.86	20.86	43.77	43.77
7	112	25.38	19.51	19.51	45.51	45.51
8	119	24.06	18.82	18.82	46.16	46.16
9	126	22.87	18.10	18.10	46.58	46.58
10	133	21.74	17.33	17.33	46.71	46.71
11	136.5	21.27	16.93	16.93	46.68	46.68
12	140	20.78	16.56	16.56	46.68	46.68

NOTE: ALL DIMENSIONS ARE IN MILLIMETERS

Figure 3.3.4. Design of Propeller for Model Tests.

FIGURE 3.4.1

COMPONENTS OF PROPULSION ICE LOADS



PROPULSION LOAD = OPEN WATER HYDRODYNAMIC LOAD

+ INDIRECT ICE LOAD DUE TO THE PROPELLER WORKING IN THE HYDRODYNAMIC DISTURBANCE CAUSED BY THE PRESENCE OF ICE

+ DIRECT ICE LOAD DUE TO THE CONTACT OF THE PROPELLER WITH ICE

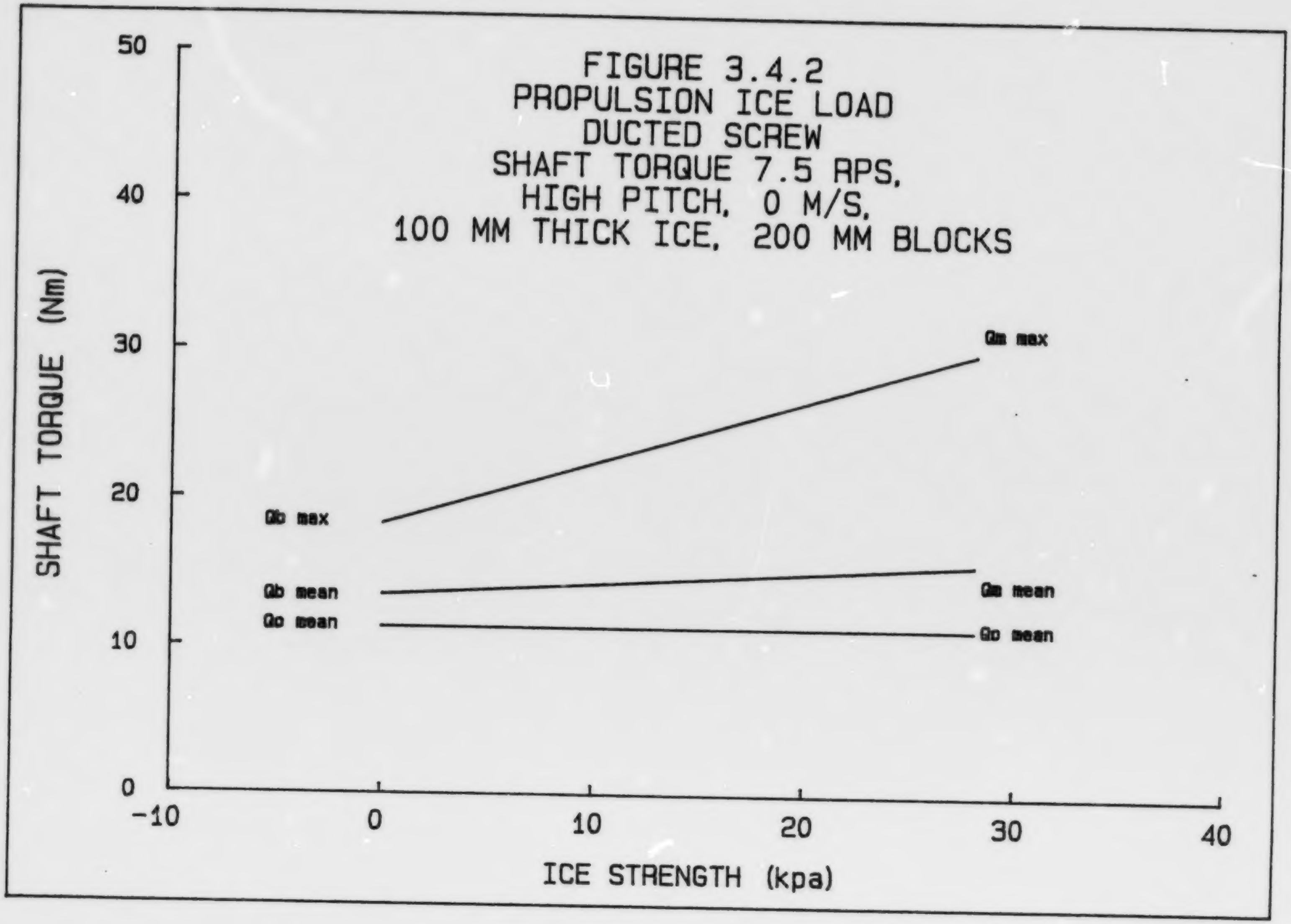


FIGURE 3.4.2
PROPULSION ICE LOAD
DUCTED SCREW
SHAFT TORQUE 7.5 RPS,
HIGH PITCH, 0 M/S,
100 MM THICK ICE, 200 MM BLOCKS

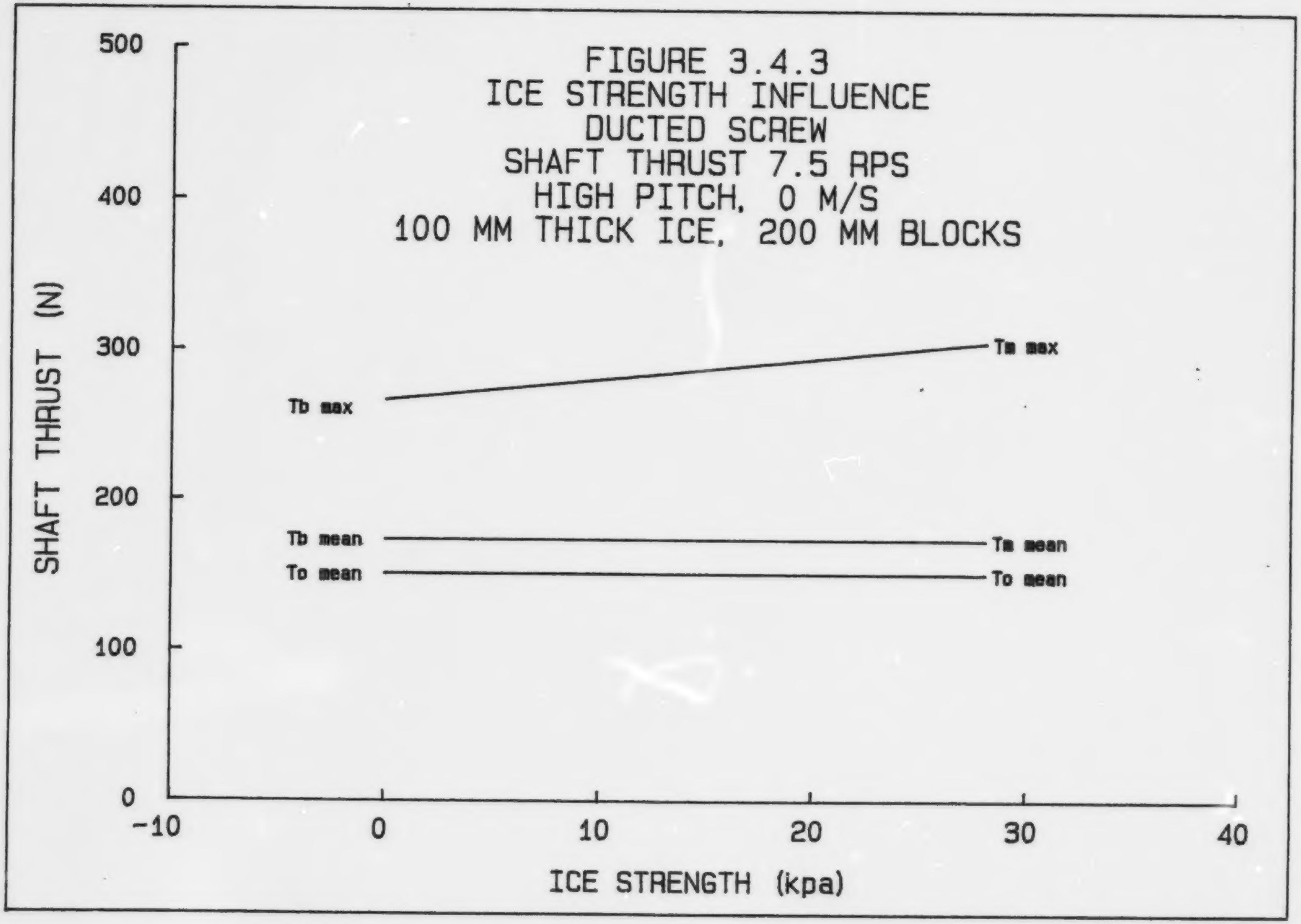
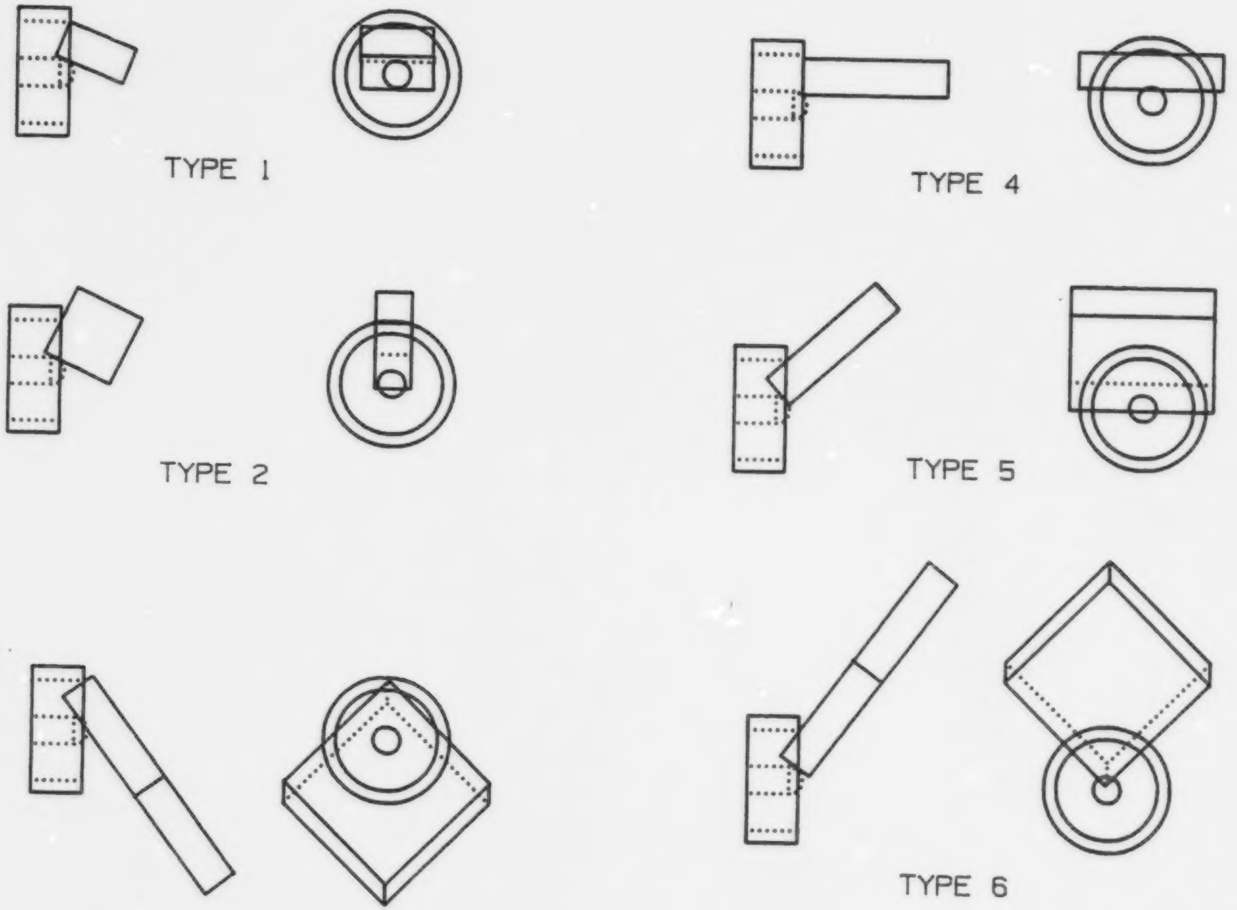


FIGURE 3.4.3
ICE STRENGTH INFLUENCE
DUCTED SCREW
SHAFT THRUST 7.5 RPS
HIGH PITCH, 0 M/S
100 MM THICK ICE, 200 MM BLOCKS

FIGURE 3.4.4

ICE BLOCK BLOCKAGE TYPES



TYPE 1

TYPE 4

TYPE 2

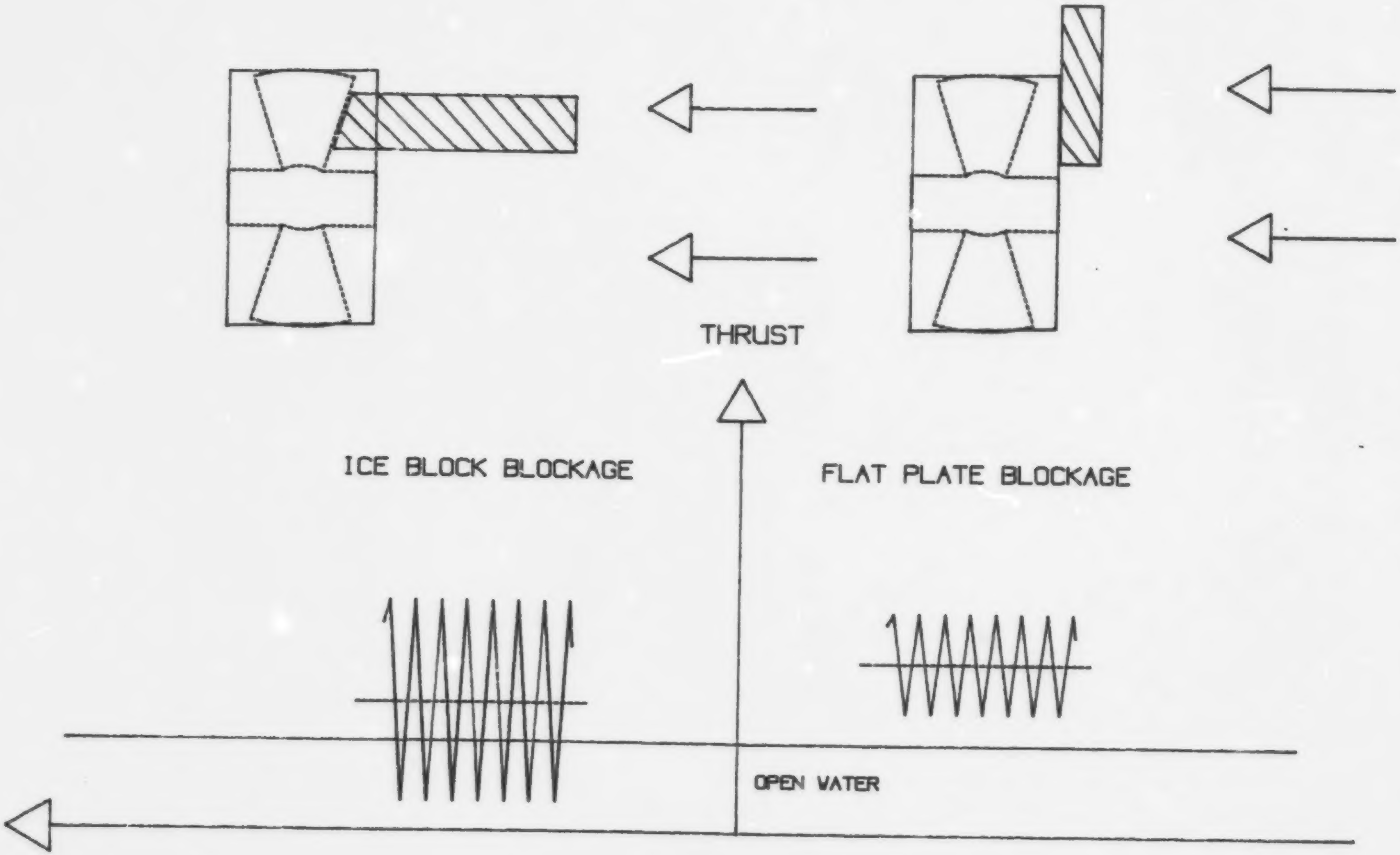
TYPE 5

TYPE 3

TYPE 6

FIGURE 3.4.5

INFLUENCE OF FLAT PLATE BLOCKAGE vs ACTUAL ICE BLOCK BLOCKAGE



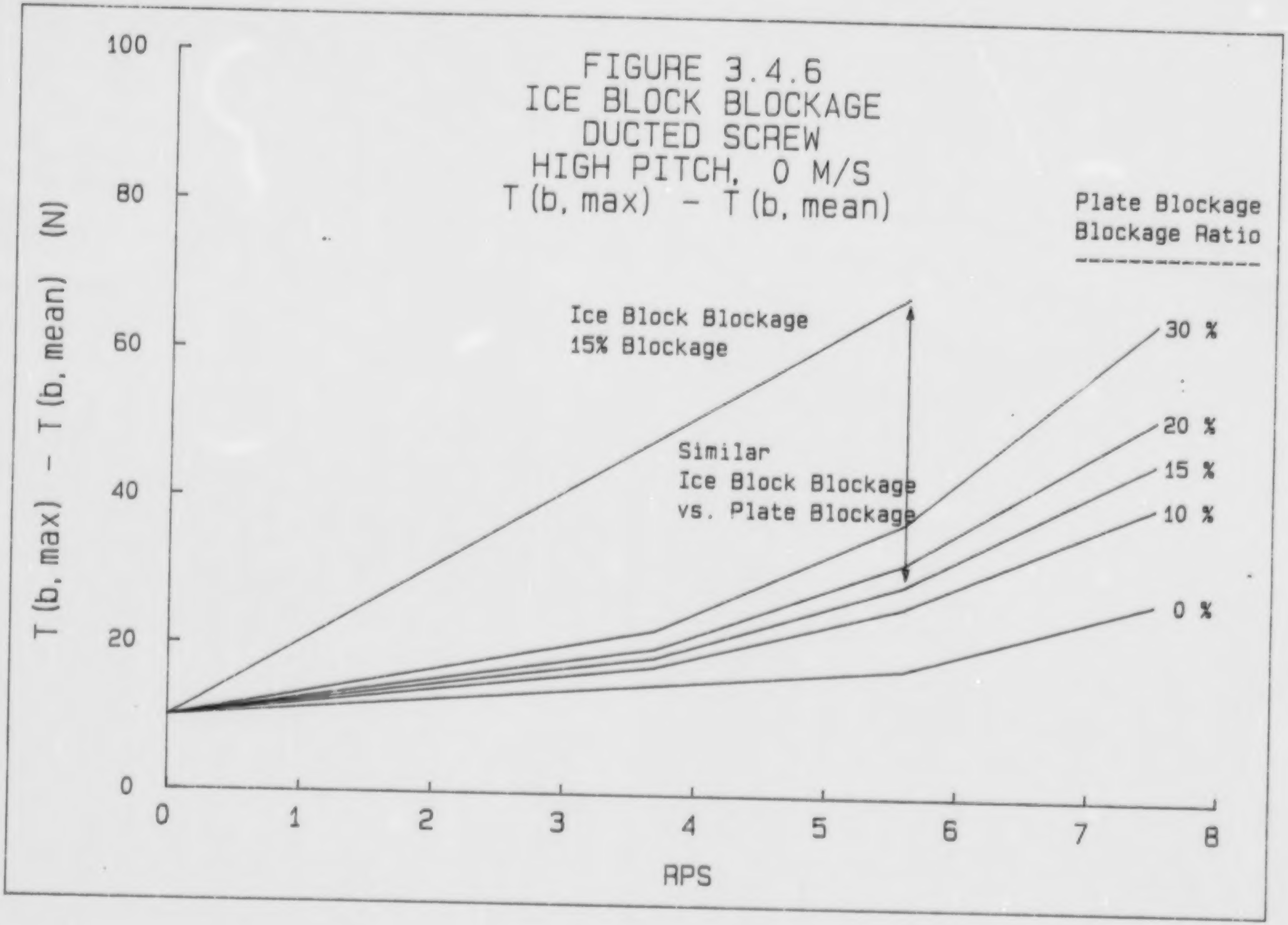
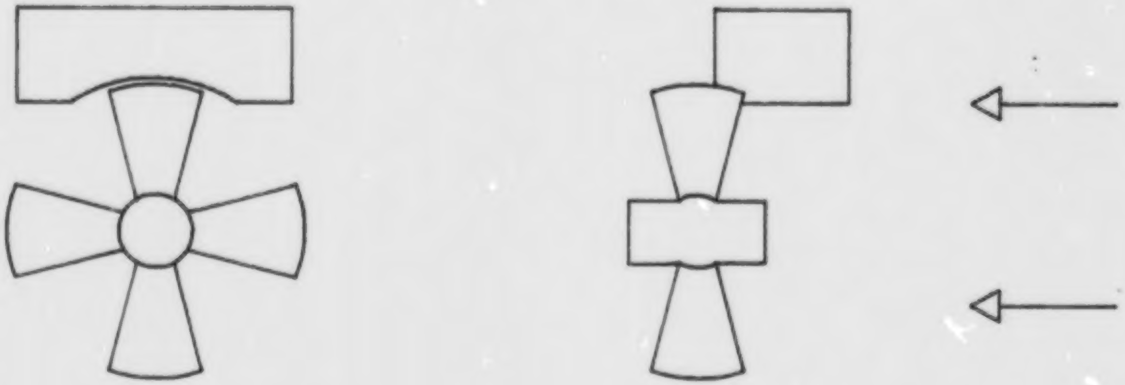


FIGURE 3.4.6
ICE BLOCK BLOCKAGE
DUCTED SCREW
HIGH PITCH, 0 M/S
T (b, max) - T (b, mean)

FIGURE 3.4.7

ICE LOADING OF OPEN PROPELLER



SHAFT LOAD = OPEN WATER

+ INDIRECT ICE LOAD OR PREMILLED

+ DIRECT ICE LOAD OR MILLING

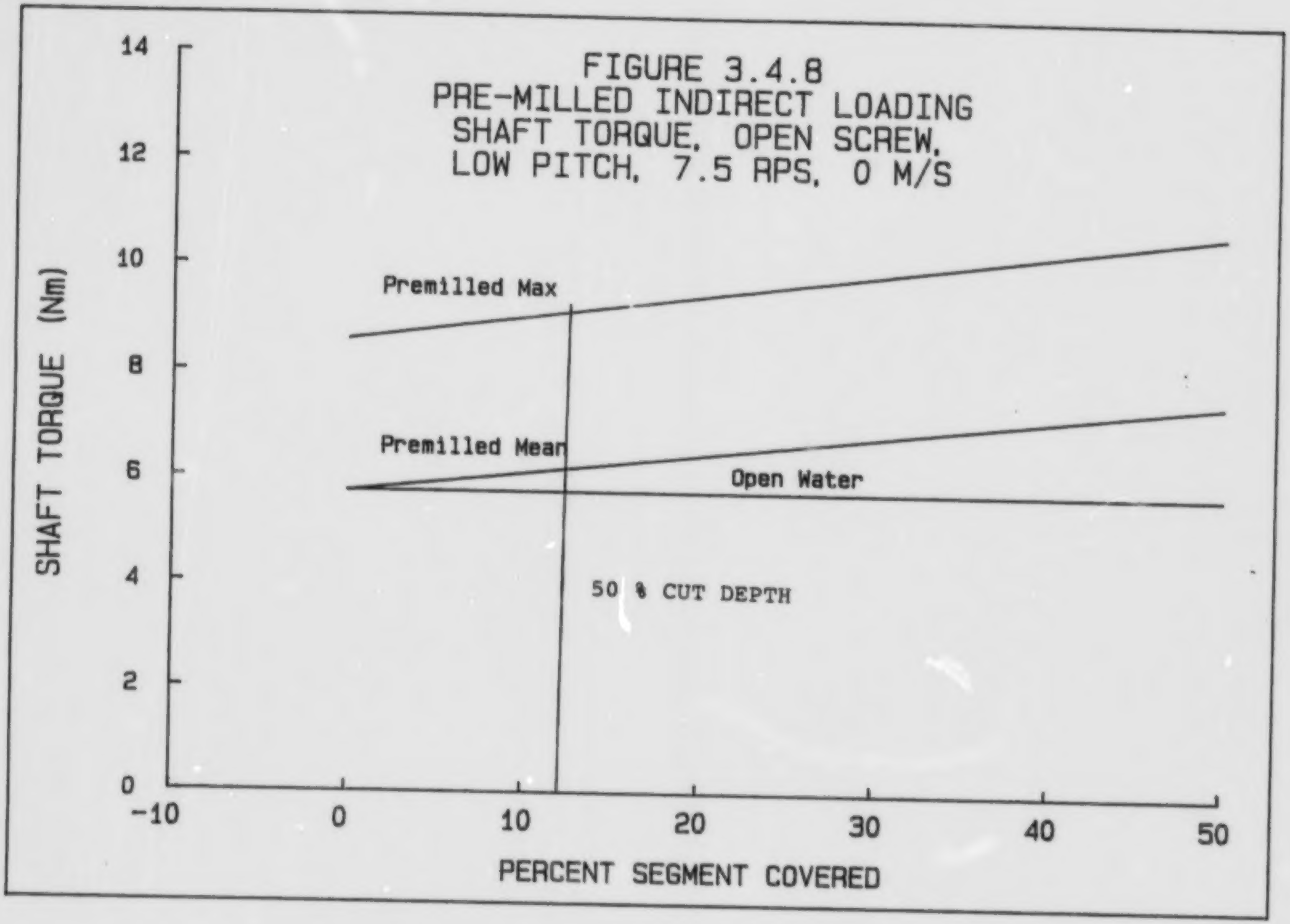


FIGURE 3.4.8
PRE-MILLED INDIRECT LOADING
SHAFT TORQUE, OPEN SCREW,
LOW PITCH, 7.5 RPS, 0 M/S

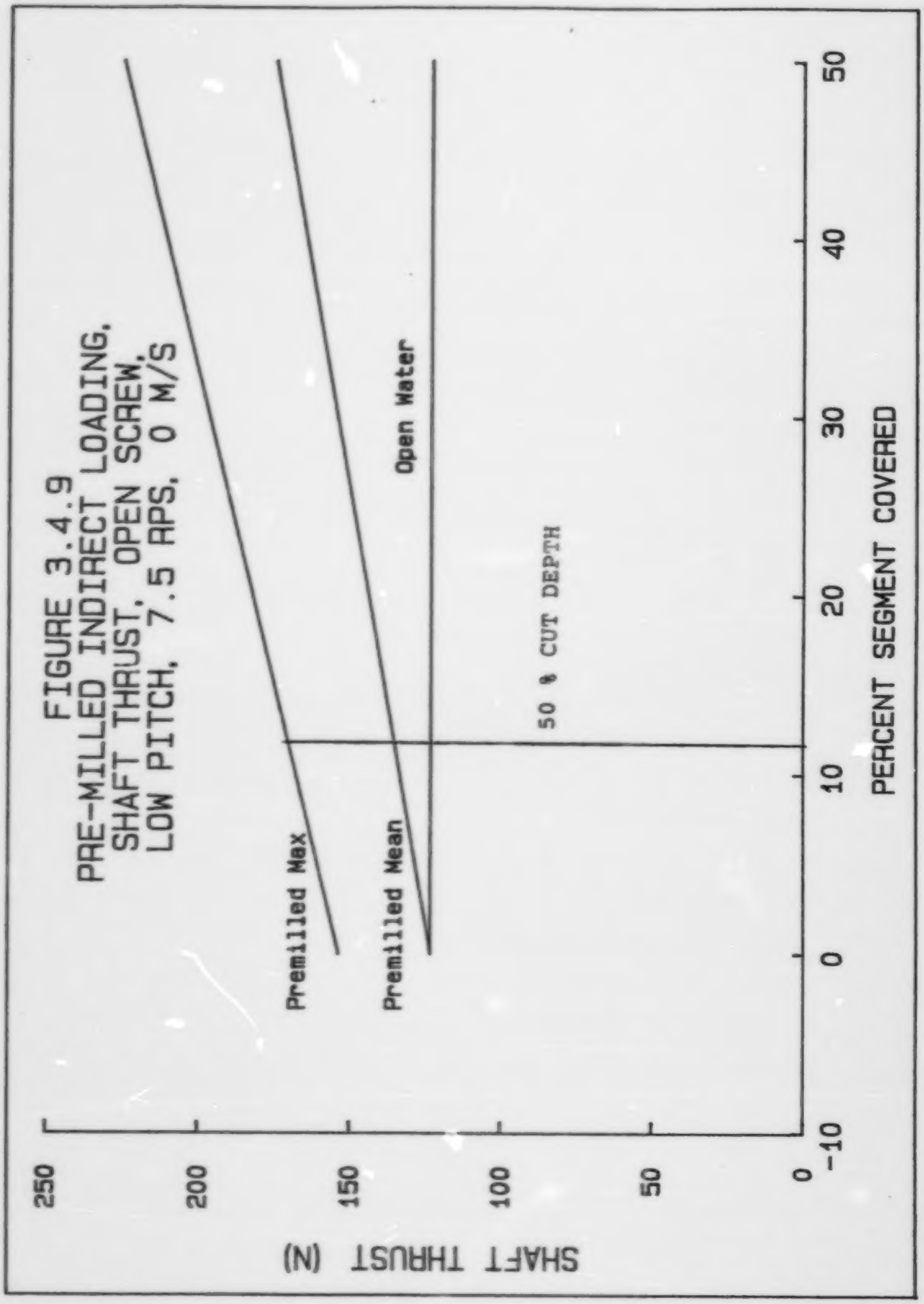


FIGURE 3.4.9
PRE-MILLED INDIRECT LOADING,
SHAFT THRUST, OPEN SCREW,
LOW PITCH, 7.5 RPS, 0 M/S

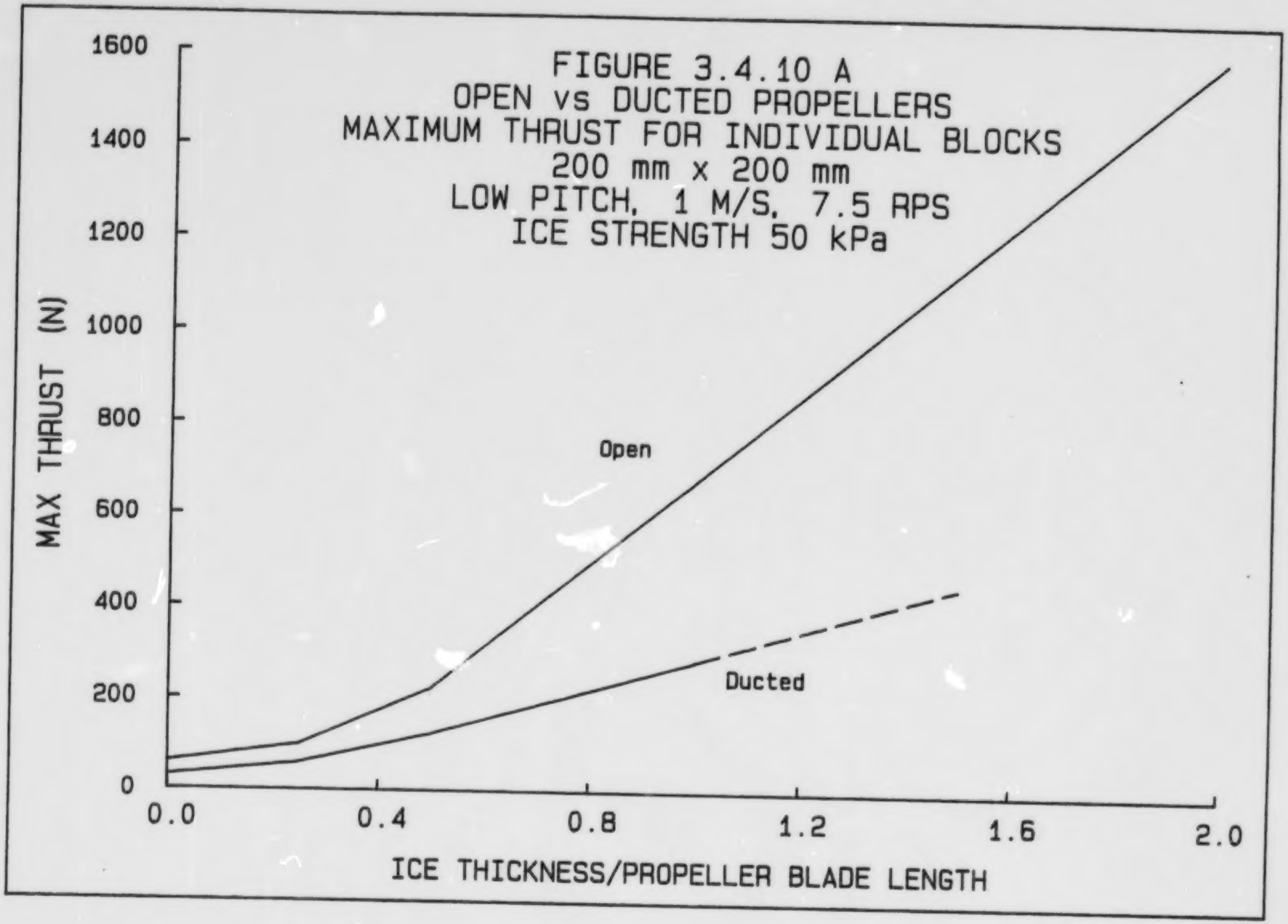


FIGURE 3.4.10 A
OPEN vs DUCTED PROPELLERS
MAXIMUM THRUST FOR INDIVIDUAL BLOCKS
200 mm x 200 mm
LOW PITCH, 1 M/S, 7.5 RPS
ICE STRENGTH 50 kPa

FIGURE 3.4.10 B
OPEN vs DUCTED PROPELLERS
MAXIMUM TORQUE FOR INDIVIDUAL BLOCKS
200 mm x 200 mm
LOW PITCH, 1 M/S, 7.5 RPS
ICE STRENGTH 50 kPa

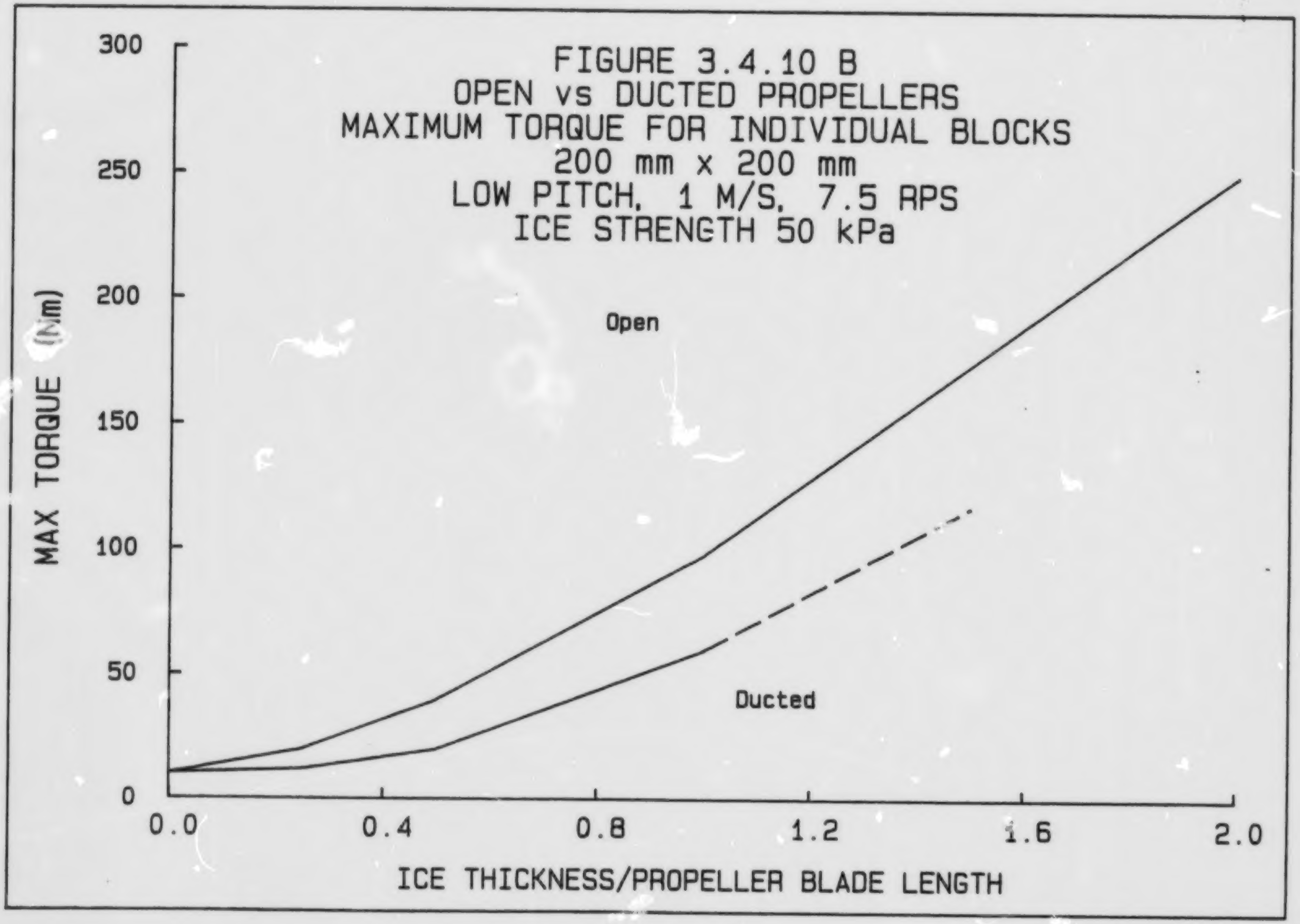
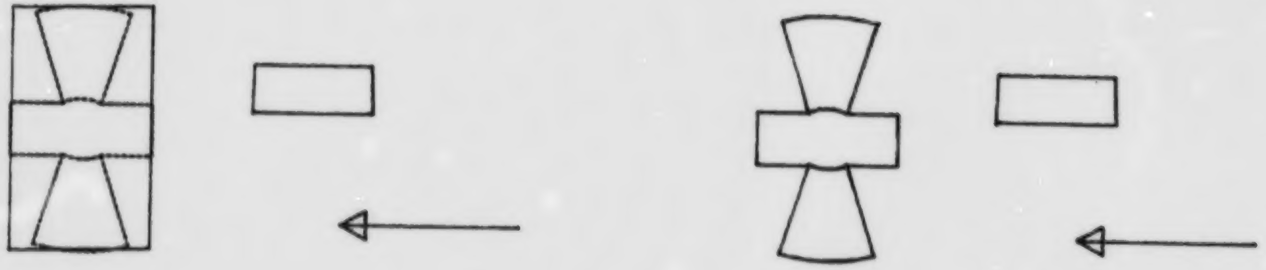


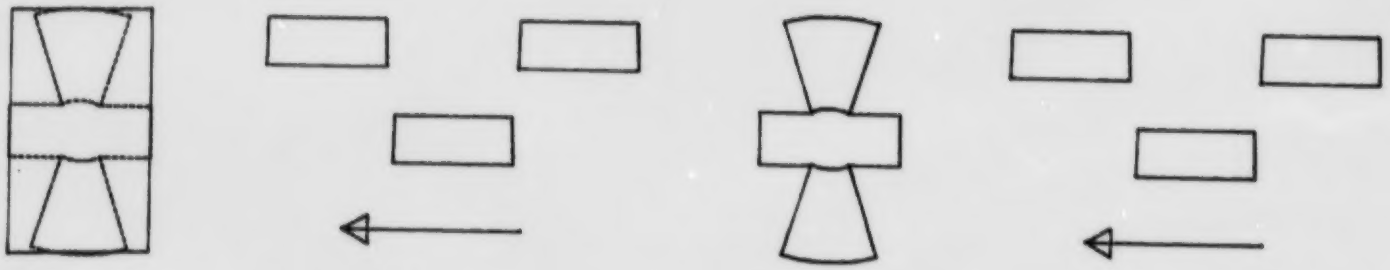
FIGURE 3.4.11

THE PRINCIPLE OF INDIVIDUAL BLOCKS vs
CONTINUOUS STREAM OF BLOCKS

INDIVIDUAL BLOCKS



CONTINUOUS STREAM OF BLOCKS



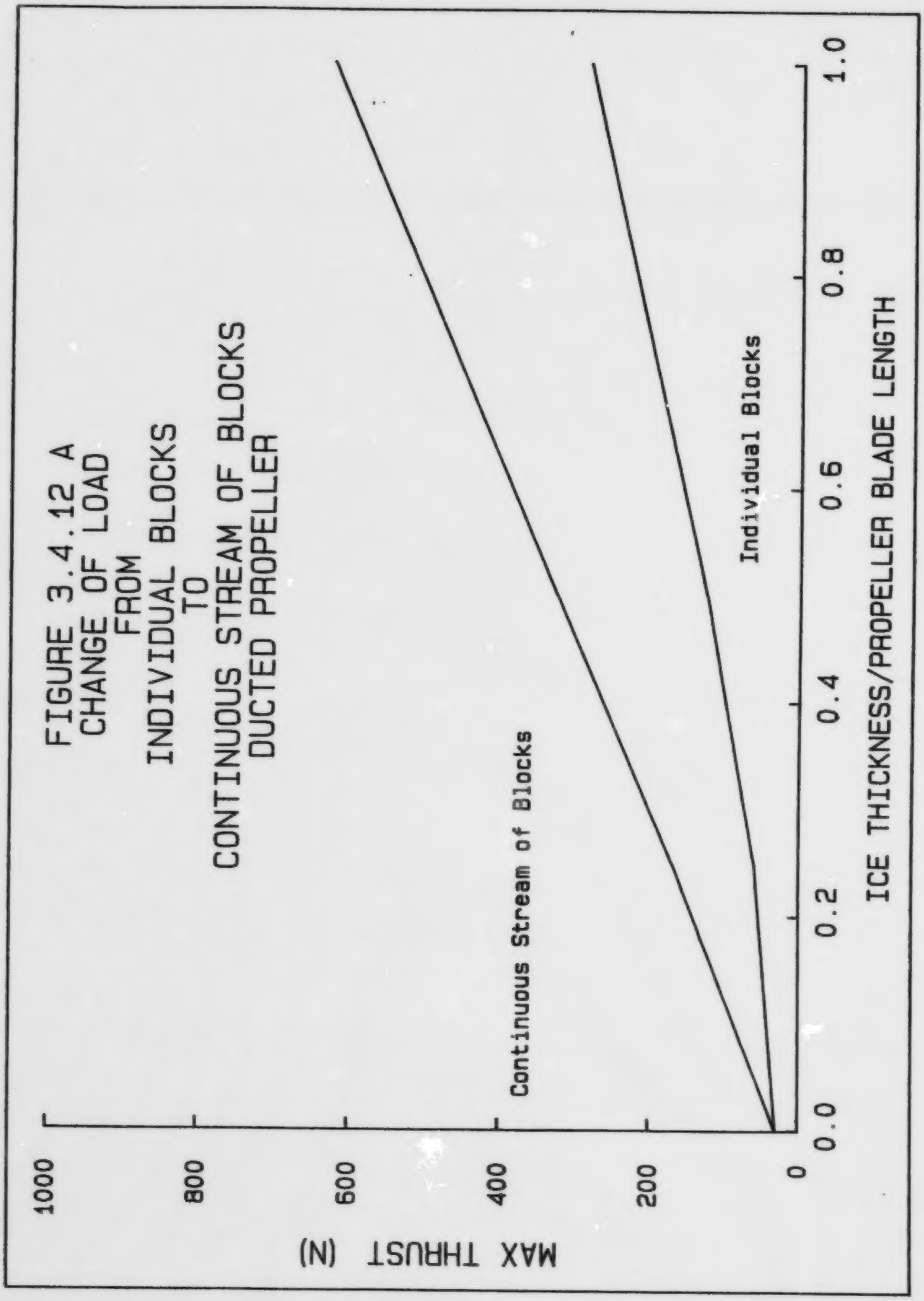


FIGURE 3.4.12 A
CHANGE OF LOAD
FROM
INDIVIDUAL BLOCKS
TO
CONTINUOUS STREAM OF BLOCKS
DUCTED PROPELLER

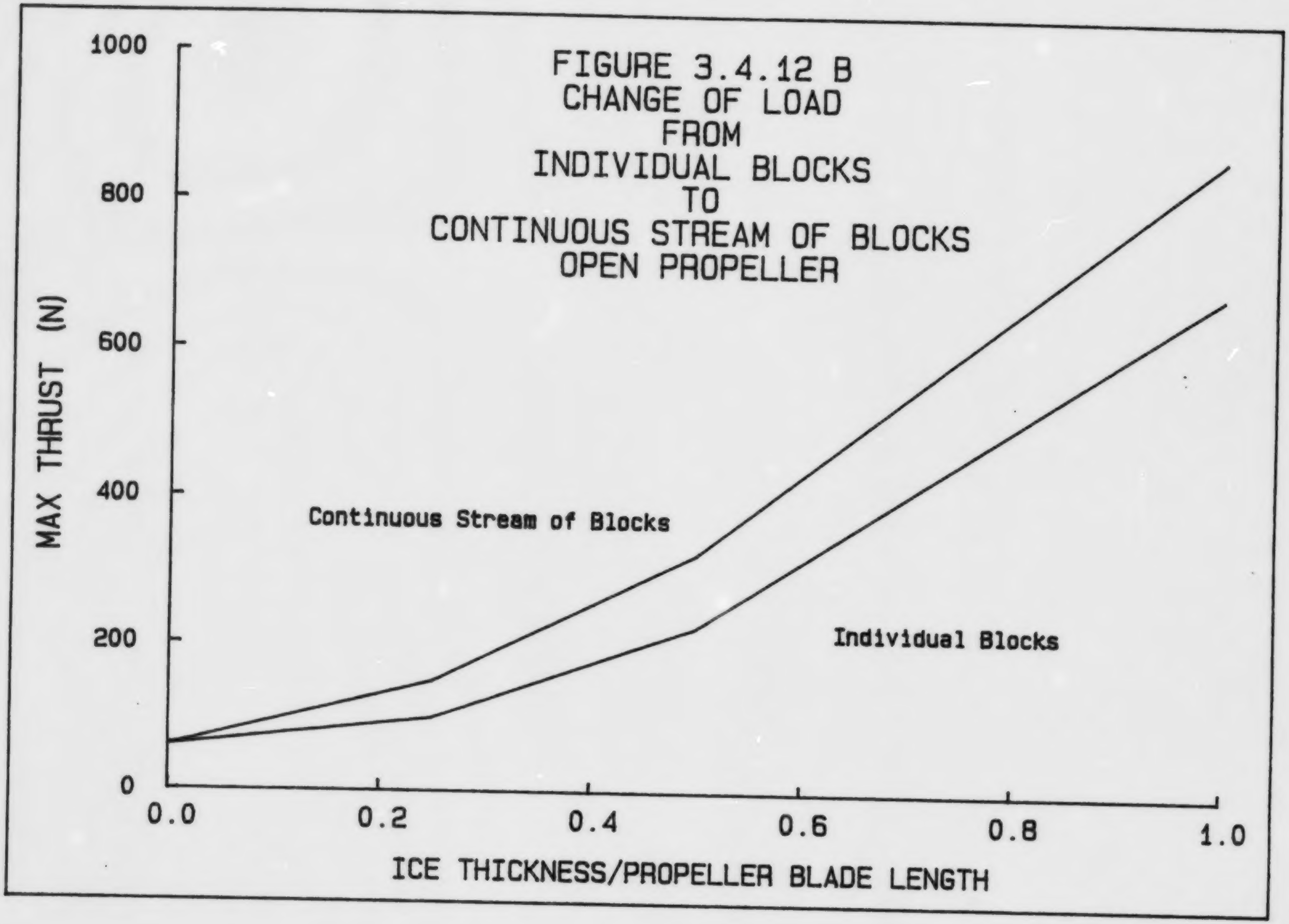


FIGURE 3.4.12 B
CHANGE OF LOAD
FROM
INDIVIDUAL BLOCKS
TO
CONTINUOUS STREAM OF BLOCKS
OPEN PROPELLER

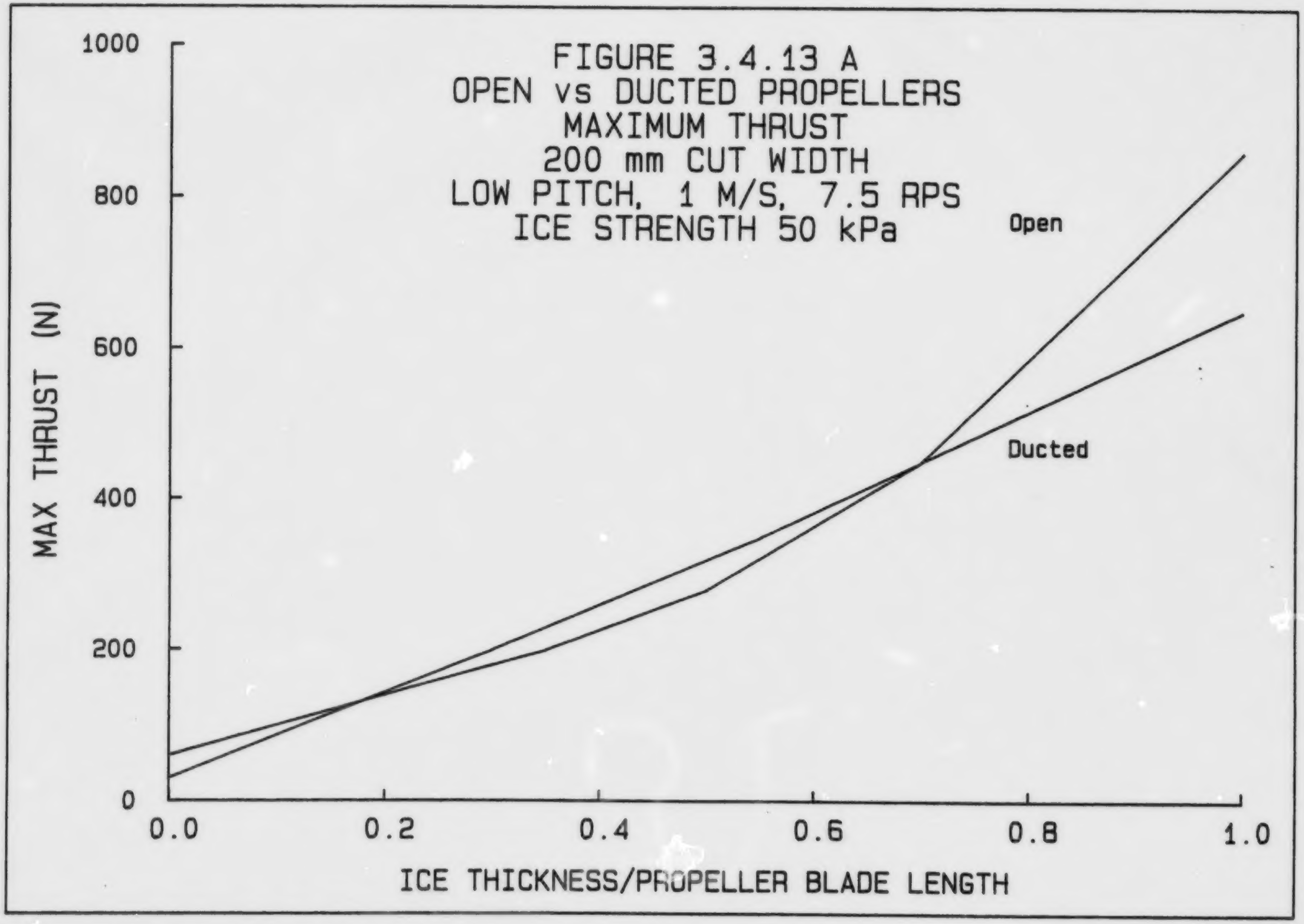


FIGURE 3.4.13 A
OPEN vs DUCTED PROPELLERS
MAXIMUM THRUST
200 mm CUT WIDTH
LOW PITCH, 1 M/S, 7.5 RPS
ICE STRENGTH 50 kPa

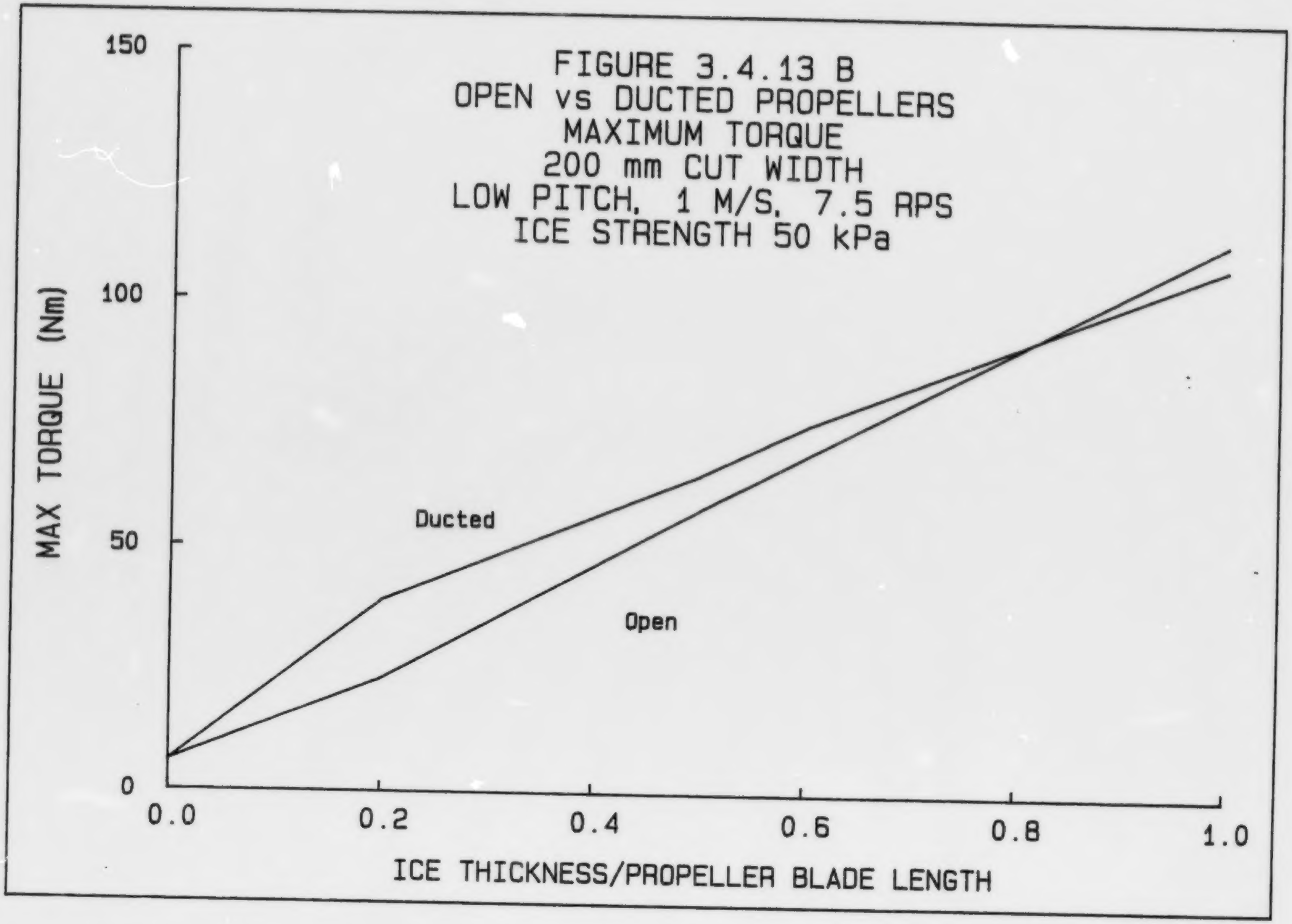


FIGURE 3.4.13 B
OPEN vs DUCTED PROPELLERS
MAXIMUM TORQUE
200 mm CUT WIDTH
LOW PITCH, 1 M/S, 7.5 RPS
ICE STRENGTH 50 kPa

4. MODEL SCALE TO FULL SCALE CORRELATION

4.1. General

The purpose of the correlation study between full scale data and model test data is twofold:

- to establish the correlation from model tests to full scale for the current and future use of model test results in the prediction of propulsion ice loads for full scale ships.
- to assess the quality of the model tests in terms of repeating similar phenomena as observed and recorded on full scale. If similar phenomena are represented, then there is better reason to trust model tests in areas where the full scale data do not exist.

The full scale data represent a very real and true small sample of propulsion loading events in terms of ice conditions and duration. Table 4.1., presents the values and compromises of full scale data. The full scale data are also associated with the particular ship design that has been tested as well as the operational procedures during the tests. Based on full scale data alone, there would be great difficulty in establishing a method of extrapolating such data to other ships, other ice conditions or other operations.

The model test data does not represent the actual truth that the full scale data represents. However, the model tests as conducted in this project, have been used to study extensively the influence of a large number of parameters on the interaction between ice and propulsion systems. Table 4.2 presents the values and compromises of the model tests in this respect. It has been possible to vary virtually all parameters involved. Moreover, it has been possible to observe the phenomena leading to the particular propulsion loading in each ice interaction. This helps establish the basic physical facts around the modeling of propulsion ice interaction.

In this project, the full scale data that are available for model to full scale correlation comparisons are for the Robert Lemeur (Section 4.3) and the Jarvsaar (Section 4.2). Each of these sets of full scale data has been assessed by itself in Chapter 2. In this chapter, that combination of parameters from the model tests which matches the known full scale trial conditions, is first determined. Then, using direct interpolation and Froude scaling, the loading estimate for full scale conditions is made.

Finally, in the last section 4.4., the meaning of the degree of correlation in each of the cases is assessed.

4.2. Jarvsaar

4.2.1. Torque comparison

There are two comparisons to be made: the maximum torque event for the nozzle propeller as well as for the open propeller. The events are as introduced in Chapter 2.

The comparison of the nozzle propeller load also includes a comparison of the ice-induced hydrodynamic load. The most severe blockage event is taken from full scale tests and compared with the estimate of blockage or ice-induced hydrodynamic load from the model tests in a similar situation.

The comparison between the model based estimate and full scale data is shown in Figure 4.1. In this Figure and the other Jarvsaar comparison Figures 4.2, 4.3 and 4.4, the full scale maximum loads and the model prediction loads include the same components. For blockage loads this is the ice induced hydrodynamic load only and for the milling load this is the ice induced hydrodynamic and direct ice loads. (i.e. open water hydrodynamic load is not included). Figure 4.1 shows that there is a reasonably good match between the full scale data and model scale prediction. In particular, the match between the ice-induced hydrodynamic loads is very good. The actual size of the ice block which caused the full scale load is not known. That is why the comparison is shown with the size of the ice block as a parameter. A factor of about 0.8 can be associated with the match of model and full scale data. This indicates that the model test prediction gives higher torques than the full scale tests.

For the open propeller, the comparison of ice loads from model test estimates and from full scale is shown in Figure 4.2. It is not possible to separate the ice-induced hydrodynamic load from the full scale data. Consequently, a comparison of indirect ice loads has not been possible. However, for the total ice load, the match between the actual full scale data and model based predictions is good. A factor of 1 for matching model and full scale data is best.

4.2.2. Thrust Comparison

Thrust comparison is not as straightforward as torque comparison. This is due to the fact that in full scale the highest thrust values were measured at a very low pitch, considerably below the values used in model tests. Also, the highest thrust events were associated with a high rudder angle (observe that the highest torque events were not associated with high rudder angle). Thus the selection of a separate sample from the full scale tests to match the model test parameters, with zero rudder angle and at similar pitch levels at which model tests were performed, is made. This however, does not represent the maximum condition in terms of thrust and is not as applicable for the purpose of establishing design loads as the torque comparison.

The comparison is shown in Figure 4.3. for the nozzle propeller and in Figure 4.4. for the open propeller.

The comparison in Figure 4.3 for the thrust maximums for the nozzle propeller show a very good match between the model test prediction and full scale data . A factor of 1 is the best representation of match.

The comparison in Figure 4.4 for the thrust maximums for the open propeller shows also a very good match between the model test prediction and the corresponding full scale data. A factor of 1 is best fitted between these two.

Both in Figure 4.3 and 4.4, the absolute maximum thrust in full scale has been measured in other conditions beyond the model test parameter range. There is a factor of about 1.5 for the highest full scale test load in comparison to the load matching the model test results for the nozzle propeller and a factor of about 1.3 for the open propeller. These factors will be used in establishing the design load conditions in the next Chapter.

4.3. Robert Lemeur

4.3.1. Torque Comparison

The selected tests from the Robert Lemeur full scale trials have been described in Section 2.2.2. It should be noted that for the Robert Lemeur, the range of variation of both ice strength and thickness is very large. Ice thickness ranges from 1m to 9m and the corresponding ice strengths from 200 kPa to 2 MPa. The full scale ice parameter values at which the ship and model correlation should be carried out have been selected on the basis of the following logical interpretation of the full scale trials events. The Robert Lemeur ducted propellers are protected from interaction with the thickest ice in any ice regime by a faired skirt or propulsion island. Moreover, on the rare occasion that very thick ice of the high strength reported might have approached the ducted propellers, these ice blocks, by virtue of their size and strength, would not be able to enter the nozzle and therefore have direct contact with the propellers. In all probability, therefore, it is the thinner and weaker ice which interacted with the propulsion system to produce the trials propulsion system measurements. It is assessed from extensive operational experience with the Robert Lemeur, that the probable thickness of ice which produced the peak loads during full scale trials was at the lower end of the thickness range, at most about 1.5m. Ice strength would be about 200 kPa and the ice blocks would typically have ariel dimensions of about 3 times ice thickness.

The torque comparison is shown in Figure 4.5. There is clearly an uncertainty or inaccuracy in this type of comparison, where the values of the two primary parameters have had to be estimated from a very wide possible range. The match between the full scale data and model based estimate is however, given the assumptions, good. This comparison shows how the value of full scale data can be seriously diminished when environmental ground-truthing is not carefully followed.

4.3.3. Thrust Comparison

The thrust comparison suffers from the same shortcomings as the torque comparison. These are the uncertainty as to full scale ice thickness and strength, and the lack of match between the model test parameters and the full scale parameters for the highest thrust events. The high thrust events occurred at low pitch, whereas the minimum model pitch was in the medium pitch range.

The full scale data selected for comparison and the corresponding model test based predictions are shown in Figure 4.6. Correlation is again good, providing that the assumptions have been correct for the selection of the low ice strength range and the ice thickness of 1.5 times blade length.

4.4. Discussion about Correlation

A good match between full scale data and model test based estimates means that the ship test conditions and total test time have caused similar loads as in the model tests. It should be noticed that the model tests represent a limited sample which is difficult to compare against any specific length of test time in full scale. However, a good match, together with observations about the likely similarity of the phenomena between model and full scale , as carried out in this project, proves that the model tests provide a good representation of ice loads caused by ice blocks of specific size and strength.

It should be noticed that the propeller used for the model tests was one of Kaplan type, which is normally only used in nozzles. In the current model tests, this propeller was used as an open propeller as well. There is no previous experience to tell how this might influence the torque or thrust load. It can be speculated that the rate of load increase related to torque might be higher for a Kaplan-type blade due to the virtually straight leading edge. The rounded tips of a normal open propeller blade may well result in a lower rate of load increase due to a more gradual contact with ice.

The detailed design of the propeller, including parameters such as the blade area ratio, sharpness of the leading edge, fit of nozzle and propeller and blade shape (skew,rake), have not been included as parameters in this study. These parameters may well have secondary influences upon the magnitude of ice loads and perhaps even upon the ice interaction mechanisms themselves. Future research should investigate this area. For the present, however, it has been shown clearly that the influence of the principal propulsion system design and operating parameters upon ice loading is well modelled, in terms of both ice interaction phenomena and magnitude of loads, in the present model ice at IMD. The match between full scale data and model test data is amazingly good.

The fact that the IMD model ice behavior has been questioned for resistance measurements for icebreaker hulls does not seem to extend, initially at any rate, into propeller and ice interaction modelling. This may well be due to the fact that the rate of loading in propeller ice interaction is much higher than in model hull icebreaking , such that the model ice behaves correctly in a brittle manner. This supposition is supported by visual observation of the distribution of ice block sizes in the channel during the model tests. Although no measurements were made, it was observed that the model channel looked very similar to that behind a ship after ice has passed through the propeller.

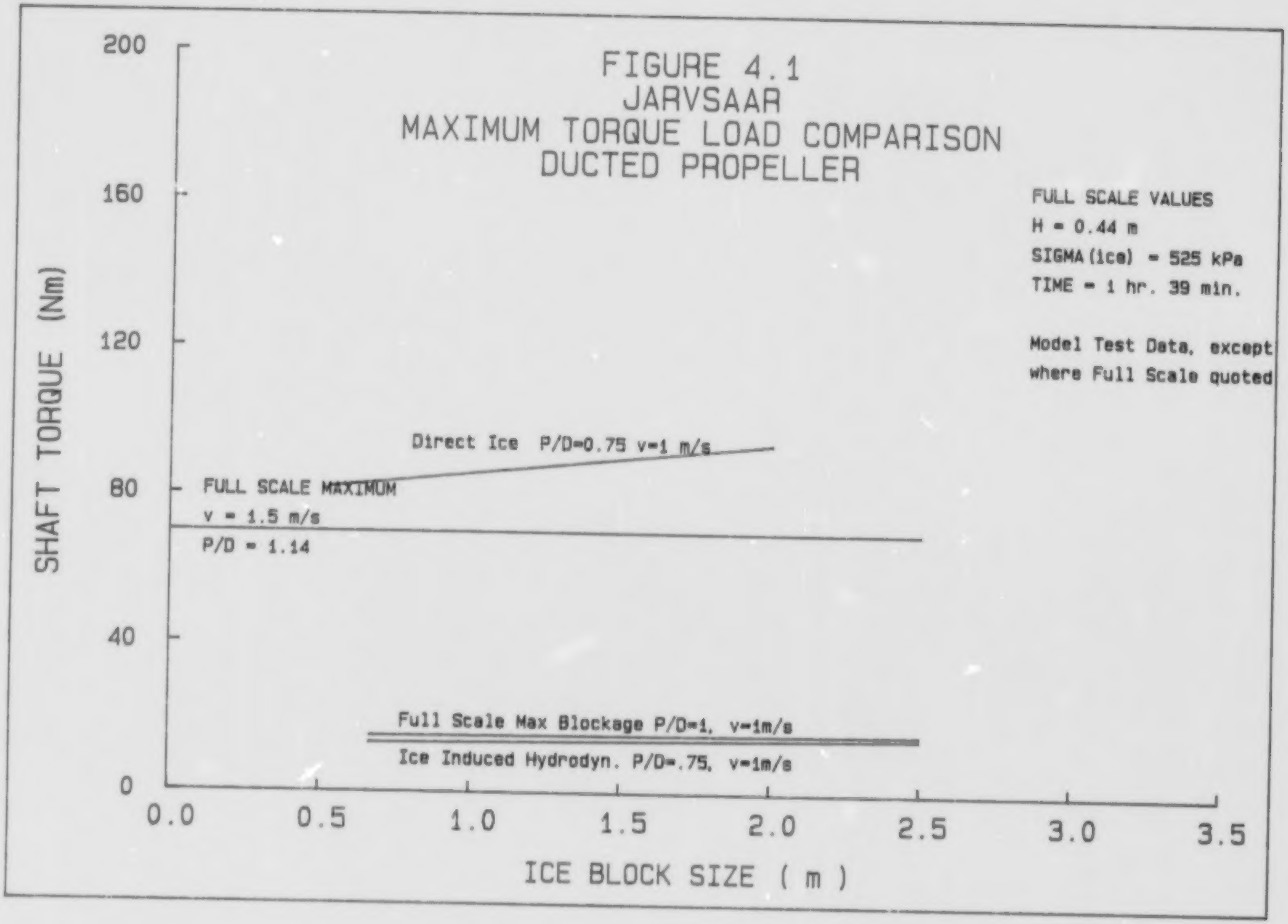


FIGURE 4.1
JARVSAAR
MAXIMUM TORQUE LOAD COMPARISON
DUCTED PROPELLER

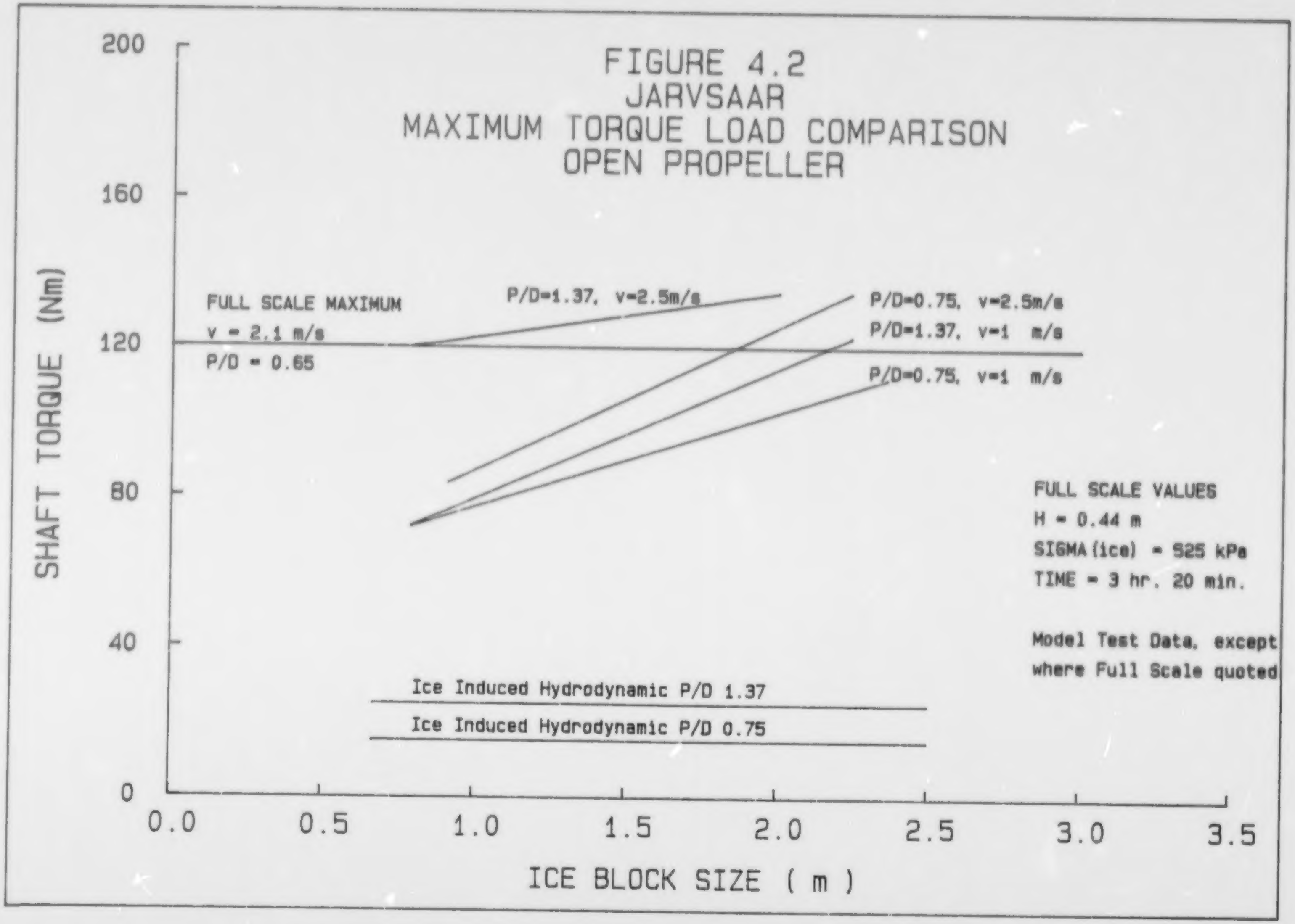
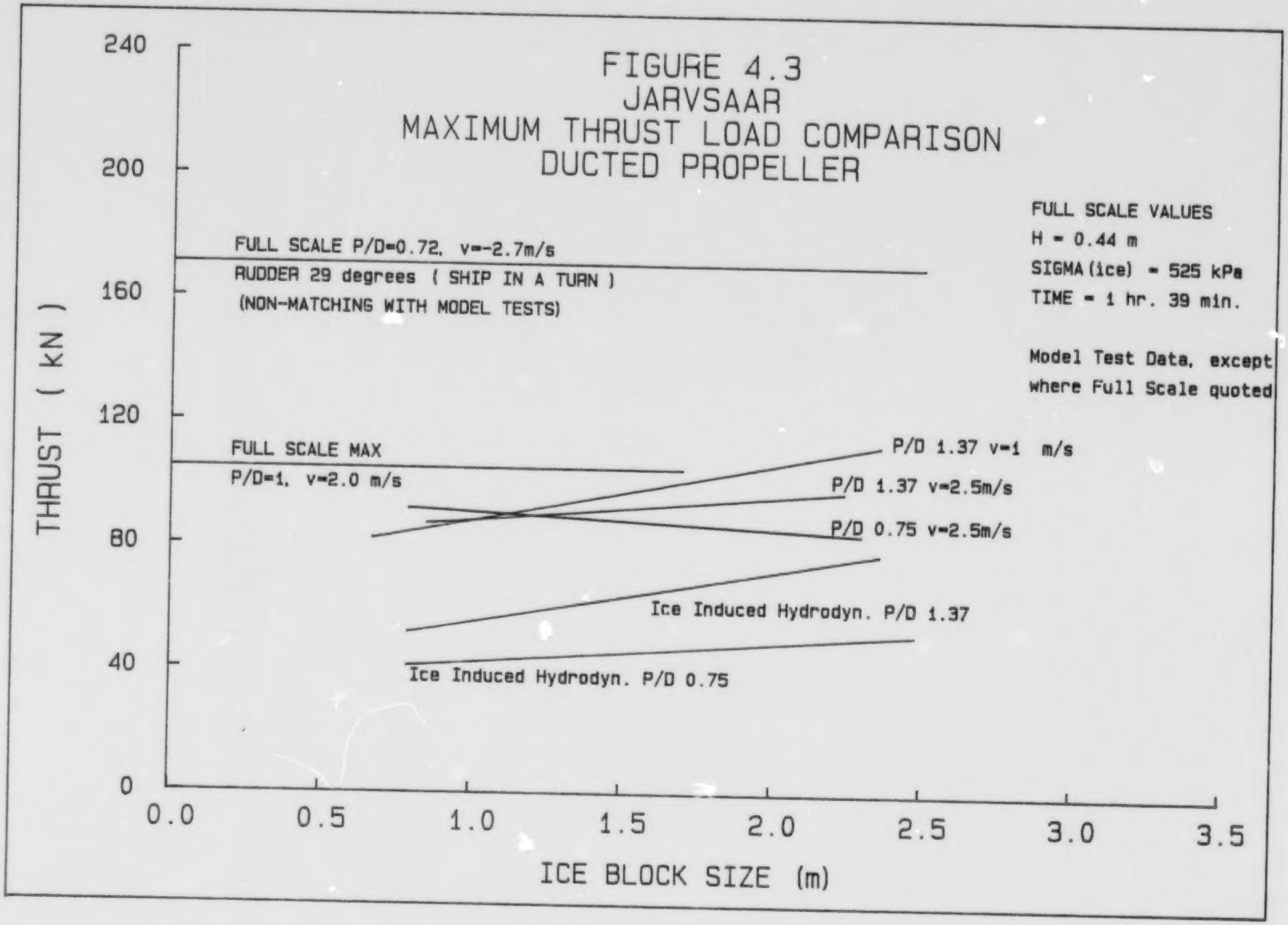


FIGURE 4.2
JARVSAAR
MAXIMUM TORQUE LOAD COMPARISON
OPEN PROPELLER

FIGURE 4.3
JARVSAAR
MAXIMUM THRUST LOAD COMPARISON
DUCTED PROPELLER



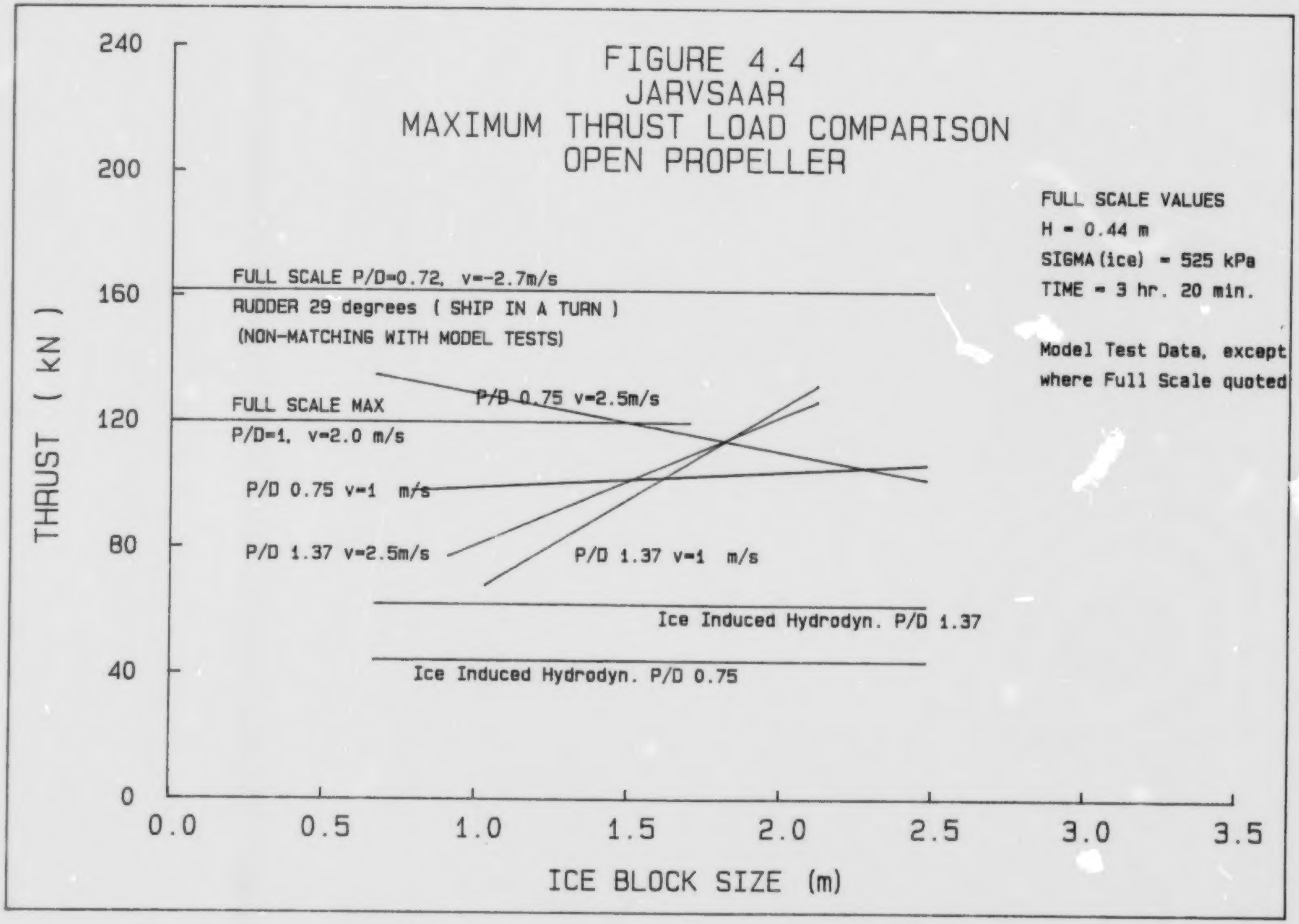


FIGURE 4.4
JARVSAAR
MAXIMUM THRUST LOAD COMPARISON
OPEN PROPELLER

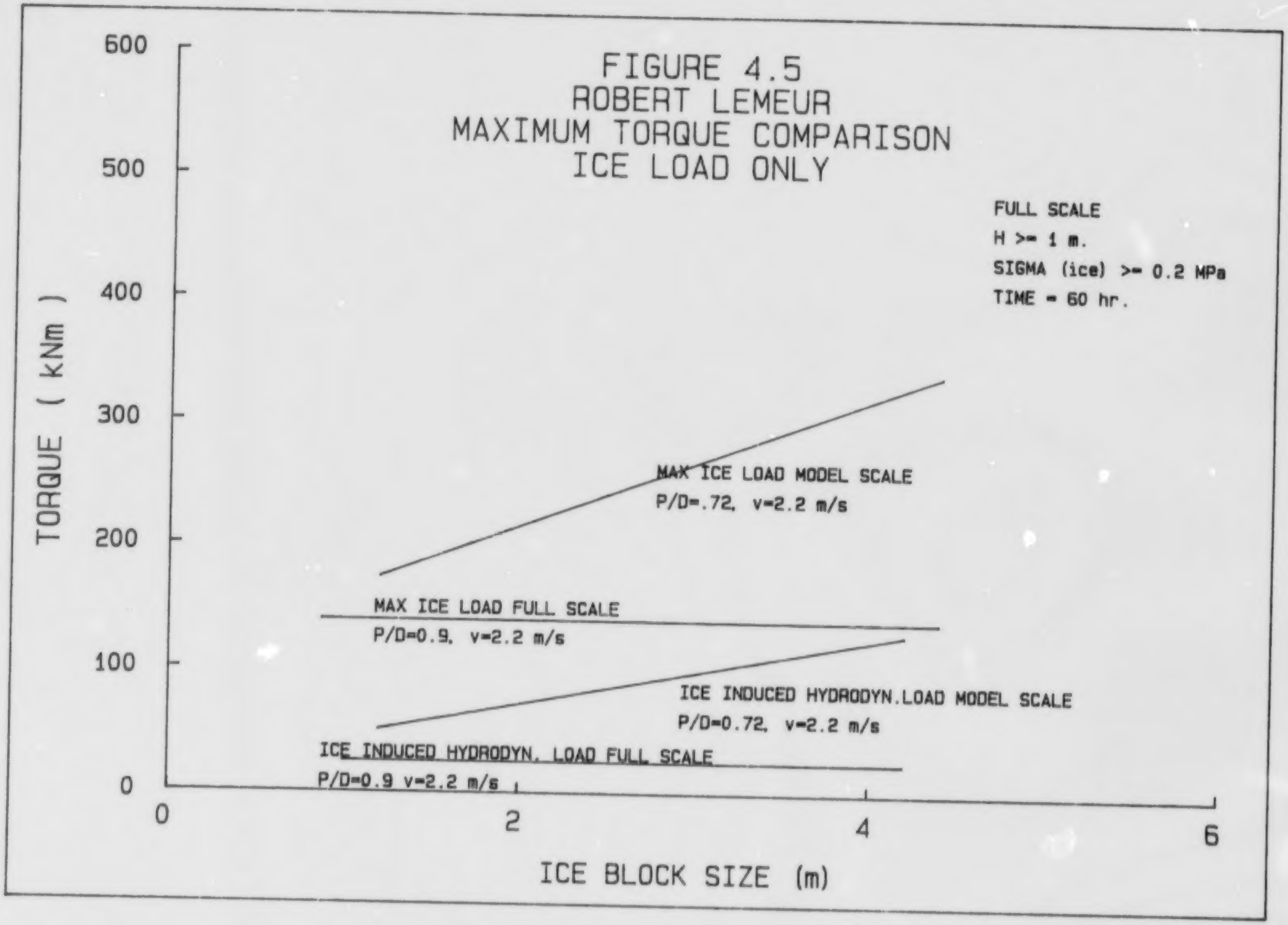


FIGURE 4.5
ROBERT LEMEUR
MAXIMUM TORQUE COMPARISON
ICE LOAD ONLY

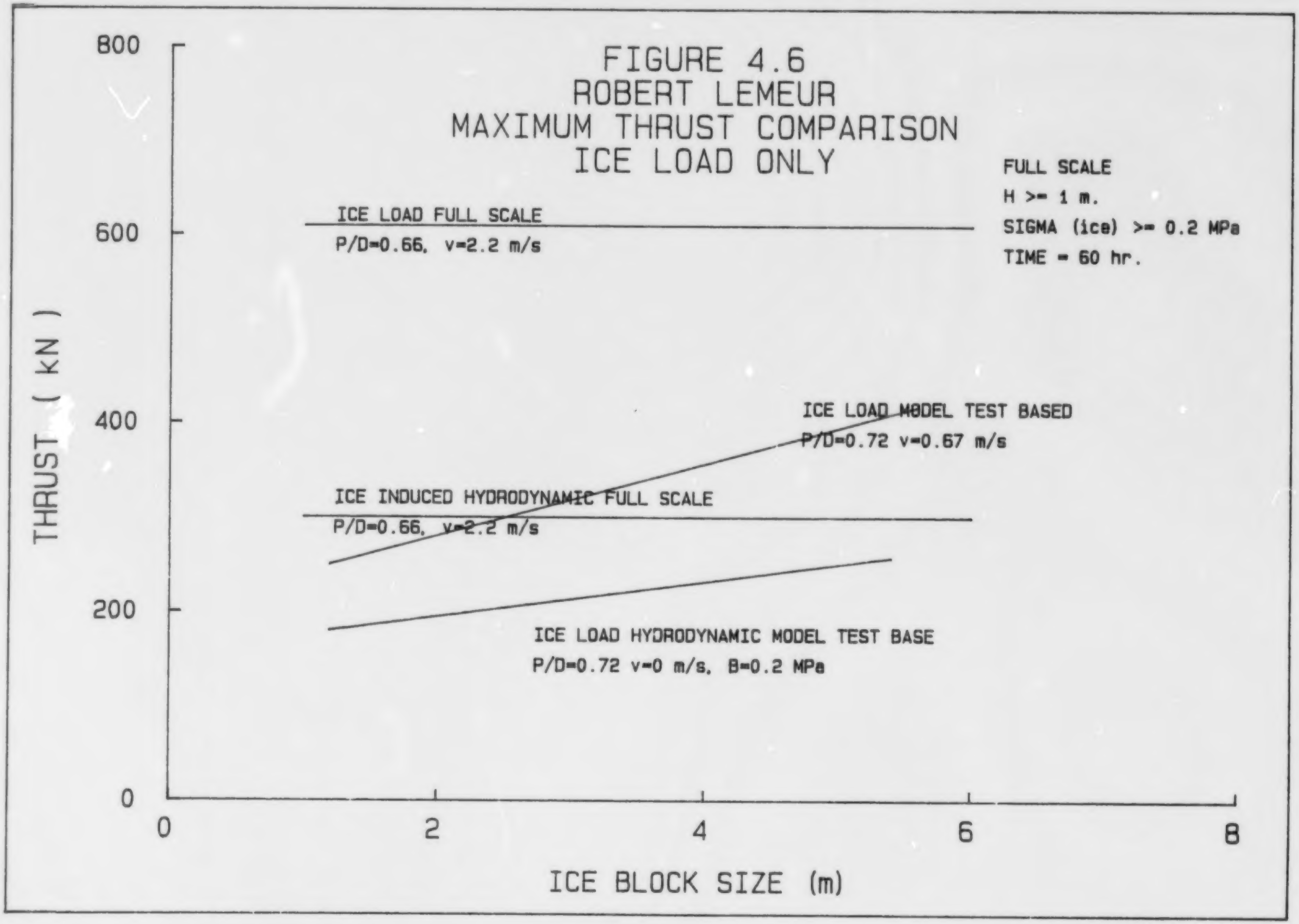


FIGURE 4.6
ROBERT LEMEUR
MAXIMUM THRUST COMPARISON
ICE LOAD ONLY

Table 4.1

PROPULSION ICE LOADS

FULL SCALE DATA

BENEFITS

- REPRESENTS FULL TRUTH, INCLUDING EVERY PHENOMENA AND INFLUENCE OF ANY UNKNOWN FACTORS

LIMITATIONS

- CAN NOT MEASURE EVERY IMPORTANT PARAMETER
- CAN NOT VARY DESIGN
- ONLY LIMITED VARIATION OF ENVIRONMENT
- ONLY LIMITED VARIATION OF OPERATIONS
- CAN NOT EXTRAPOLATE WITHOUT A MATH MODEL
- EXPENSIVE

Table 4.2

PROPULSION ICE LOADS

MODEL SCALE DATA

BENEFITS

- UNDERSTANDING PHENOMENA
- VARIATION OF PARAMETERS EXTENSIVELY POSSIBLE
    - DESIGN
    - OPERATION
    - ENVIRONMENT

LIMITATIONS

- REPRESENTATIVENESS OF REALITY NOT KNOWN WITHOUT FULL SCALE DATA
- SOME PHENOMENA NOT MODELABLE
    - REYNOLDS NUMBER
    - ICE PROPERTIES

5. DESIGN LOADS

5.1. General

Illustration of the design loading concept is presented in Figure 5.1. The input required for determination of the design loads, or rather design loading spectra, is of three types: first, data to determine ice loads on a propulsion system due to specific ice interactions: second, data to determine the type and extent of ice interaction in terms of the ship design: and third, data on the operational profile of the vessel in terms of the duration and manner of operation in different ice conditions. The combination of these many factors leads to a random distribution of loading over the lifetime of the ship. There is no single design load, but a load spectrum which constitutes the design loading. The loading on the propulsion system is a combination of various kinds of load occurrences in a full range of actual ship operations and operating conditions, and is influenced by the design of the ship as it affects ice interaction and subsequently propulsion system loading. This builds a load distribution over the lifetime of a ship, which is defined here as design loading.

This project deals specifically, and in some depth, with the first component of design loading. The input resulting from this work are mathematical formulae which predict the loading level on a propulsion system due to specific ice interactions.

The second component of establishing the influence of ship design on ice interaction and the third component incorporating the operational profile of the vessel have not been part of this project. However, in order to demonstrate the concept of the design load as the combination of the three components, an example from the trawler Jarvsaar is given below in Section 5.2. The example illustrates the concept through using a limited sample of full scale load data to arrive at design loading over the lifetime of a ship.

There is some evidence of sudden, very high loadings occurring on open propulsion systems in ice. This has caused sudden loss of blades on propellers. This has clearly not occurred as a consequence of an accumulation of load events leading to fatigue damage, but more as the result of a rare occurrence which has loaded the blades far beyond their design limit. Although these events have never been witnessed, it is suspected that the loss of blades may have occurred when the open fixed pitch propellers were being operated at very low RPM, stopped or actually slightly reversed in rotation to the movement of the ship. Such load cases have not been simulated in the current model tests, and it is therefore not possible to assess the relative severity of ice interaction with slowly rotating or stopped propellers.

The design load definitions developed in this Report contain those loading parameters which the study has shown to be important to the design of icebreaker propulsion systems. Thrust and torque only are considered here. However, in the light of indicated parametric dependencies, it appears that the blade loads and the shaft bending responses depend on the same parameters as do thrust and torque.

Design loading is approached at two levels. First, the main parameters which determine the highest loads in specific types of ice interaction are introduced. Second, the propulsion system loading distribution or spectrum is introduced to the degree that it is possible without specific knowledge of a ship design and its operational profile.

Section 5.3 gives loads for a propulsion system in a given ice thickness and strength, as well as propulsion parameter variations. This is both for open and ducted propeller.

Section 5.4 Discusses the results from the formulas.

5.2. Concept of Design Load

The concept of the design load being a distribution rather than a specific load is illustrated using full scale data from the trawler Jarvsaar. Figure 5.2, presents the torque loading for the full scale tests of the Jarvsaar. This load distribution represents 1.65 hours of operations in the specified ice conditions. The actual operational profile of Jarvsaar is not known. However, it is assumed that the ship will operate 50 hours per year in similar ice conditions for every year of its assumed 20 year lifetime.

The extrapolation of the load distribution from the full scale tests to the lifetime load distribution is carried out by adjusting the logarithmic-linear distribution of ice loads from the short time period of the tests to the lifetime of the ship. This is shown in Figure 5.3., where it is assumed that the shape of the distribution remains the same for the lifetime as it was for the test period. The number of events in each load category is multiplied by the lifetime factor of 606. The higher, solid bars, indicating a higher number of load events in each category, associated with the constant distribution shape, demonstrate how the next higher load level categories become evident. Although not measured during limited measurements in full scale, these highest loads of low probability can nevertheless be predicted in this manner from a relatively small sample of full scale data.

The example above, from one set of full scale data, is one where the test results are extrapolated statistically to the lifetime of the ship, as shown in Figures 5.2 and 5.3. It is not within the scope of this current project to determine all aspects of design load prediction for a specific ship, propulsion system and operational profile. However, Figures 5.2 and 5.3 demonstrate how the information required to achieve this can be processed once the building blocks are known. This current project addresses the fundamental building block of propulsion system and ice interaction for a wide range of propeller and ice parameters.

5.3. Loads on Propulsion from a Specific Interaction

The dependency of design loading on the parameters of the propulsion system are developed based on the model tests, as reported in APPENDIX A.

The load from the ice is separated into two components as has been done throughout the model test data analysis. The first component is the ice induced hydrodynamic load. This is expressed as the difference between the average hydrodynamic load in icefree conditions and the maximum load peak in ice blockage conditions.(For the open propeller, blockage is described in this report as the premilled condition). The direct ice load is expressed as the difference between the maximum load from ice interaction and the maximum blockage load.

The design load equation has been directly determined from the model tests with single ice block interaction, due to their successful prediction of Jarvsaar loads (and good indications of ability to predict Robert Lemeur loads). The following torque ice loading formula has been determined for the ice-induced hydrodynamic load for the ducted propeller:

$$Q_{bmax} - Q_{omean} = 0.00053 * (H/L)^{0.7} * RPM^{1.3} * D^{4.5}$$

where Q_{bmax} = maximum blockage torque (kNm)
Q_{omean} = mean open water torque (kNm)
H = ice thickness (m)
L = propeller blade length (m)
RPM = shaft revolutions (revs/minute)
D = propeller diameter (m)

For thrust, the following equation has been determined:

$$T_{bmax} - T_{omean} = 0.00031 * (H/L)^{1.2} * RPM^{1.7} * D^{4.2}$$

where T_{bmax} = maximum blockage thrust (kN)
T_{omean} = mean open water thrust (kN)

For the direct ice load for the ducted propeller, the following equation has been determined:

$$Q_{imax} - Q_{bmax} = 0.036 * \delta * (H/L)^{2} * D^{3}$$

where Q_{imax} = maximum direct ice torque (kNm)

Again for thrust, direct ice load the following load equation has been determined:

$$T_{imax} - T_{bmax} = 0.05 * \delta * (P/D)^{-1.4} * D^{2}$$

where T_{imax} = maximum direct ice thrust (kN)

The loads are also shown in Figures 5.4 - 5.5, for ice-induced hydrodynamic load and in Figures 5.6 - 5.7, for direct ice load, for a range of propeller and environmental conditions.

For the open propeller, the corresponding equations are, for the ice-induced hydrodynamic load:

$$Q_{pmax} - Q_{omean} = 0.00024 * RPM^{1.3} * D^{5.5}$$

where Q_{pmax} = maximum premilled ice-induced load (kNm)

$$T_{pmax} - T_{omean} = 0.00014 * RPM^{1.7} * D^{4.3}$$

where T_{pmax} = maximum premilled ice-induced load (kN)

and for the direct ice load:

$$Q_{imax} - Q_{pmax} = 0.03 * \delta * H/L^{2.8} * D^{4}$$

$$T_{imax} - T_{pmax} = 0.056 * \delta * H/L^{4} * D^{3}$$

The loads for the open propeller are shown in Figures 5.8 - 5.9, for the ice-induced hydrodynamic torque and in Figures 5.10 -5.11, for direct ice torque.

The loads given by the above equations and as shown in Figures 5.4 -5.11, are now the load dependencies as determined from model test parametric variations and direct scaling of model test results.

5.4. Discussion about loads

In section 5.3, formulae have been determined for the propeller and ice interaction loads of thrust and torque for both open and ducted propellers in single block ice interactions. These formulae are derived from model test data and predict both direct and indirect components of ice induced load in terms of the important governing parameters as established in this project. These are ice thickness, propeller diameter, ice strength (for direct ice loads), shaft revolutions (for indirect loads) and pitch ratio (for direct ice thrust load) as well as open and ducted configuration of the propeller. These load formulae predict maximum loads within the range of parametric variation covered by the model tests (which is clearly shown in APPENDIX A).

Prediction of actual loads for individual ice block interaction on ship scale is best achieved through comparison of loads calculated from these formulae with well documented full scale data. This procedure has been carried out and is described in Chapter 4, with particular emphasis on the Jarvsaar data, which provide an excellent and unique combination of instrumented measurement and visual record for both open and ducted propellers.

Jarvsaar full scale data comparisons suggest that the highest input loads from the specific ice interactions, as tested on model scale, have been very close to those from the model tests for the open propeller and again very close for the indirect ice load on the ducted propeller. The nozzle propeller direct ice load, as predicted from the model-based formula, was about 20 per cent higher than corresponding full scale data. This suggests that the indicated load from the equation for ducted propeller direct ice torque load is somewhat higher than a real life load.

It has also been demonstrated from the correlation exercise in Chapter 4, that the thrust loads in formulae for the maximum direct thrust ice load are not representative of the maximum levels experienced in full scale. Full scale data show that maximum propeller and ice interaction thrust loads occur at low pitch levels which were not covered in the model tests and are therefore not represented in the prediction formulae. Moreover, in those cases from the model tests where the independent influence of pitch on thrust loading could be determined, a strong influence of increasing load with decrease in pitch was found. The low pitch area is clearly an important one for future investigation both on model scale and ship -model correlation.

Other than the extremely encouraging numerical comparison of propulsion ice loads between model and full scale, this project has also demonstrated clearly the physical similarity between propeller and ice interaction, as simulated in the laboratory and as happens with much larger propellers in the real ice environment. This combination of physical and numerical similarity shows that completion of the physical parameter range on model scale and associated full scale correlation should provide and excellent predictor for propulsion ice loads in single ice block interaction. Using the Jarvsaar data, this predictor would be reliable for propellers of up to two and possibly three meters in diameter. Well documented data for appreciably larger diameter propellers of both open and ducted configuration are however now available and would serve to establish the reliability and correlation factors for the predictor equations over a much wider range of propeller diameters and ice thicknesses.

Prediction of the full scale propulsion loads for individual ice block interactions does not, as stated previously, constitute prediction of design loads. It can be considered that two important steps remain. The first is to modify the individual ice block loads for the actual type and degree of propeller and ice interaction that will occur for the particular design of ship and propulsion system in its different operating conditions. The second is to assemble the loads for all operating conditions within the vessel's mission profile and carry out the statistical analysis over the vessel's lifetime as described in this Chapter.

The significance of the degree of ice interaction has been clearly demonstrated in this project by the effect of a continuous stream of ice blocks relative to individual ice blocks. It has for example been shown that the ducted propeller is very sensitive to multiple ice block interaction, the loads increasing significantly beyond single block interaction, whereas the open propeller was far less sensitive to this in the tests.

It now remains for a simple predictor to be developed whereby the degree of propeller and ice interaction is related to ship design and operation. It is considered that this propeller and ice interaction predictor is best developed using the same approach as in the current project. That is, the use of specifically designed model tests to investigate primary parameter influences and full scale correlation for ground truthing the results.

FIGURE 5.1.

PROPULSION DESIGN LOADS AND MACHINERY PROTECTION

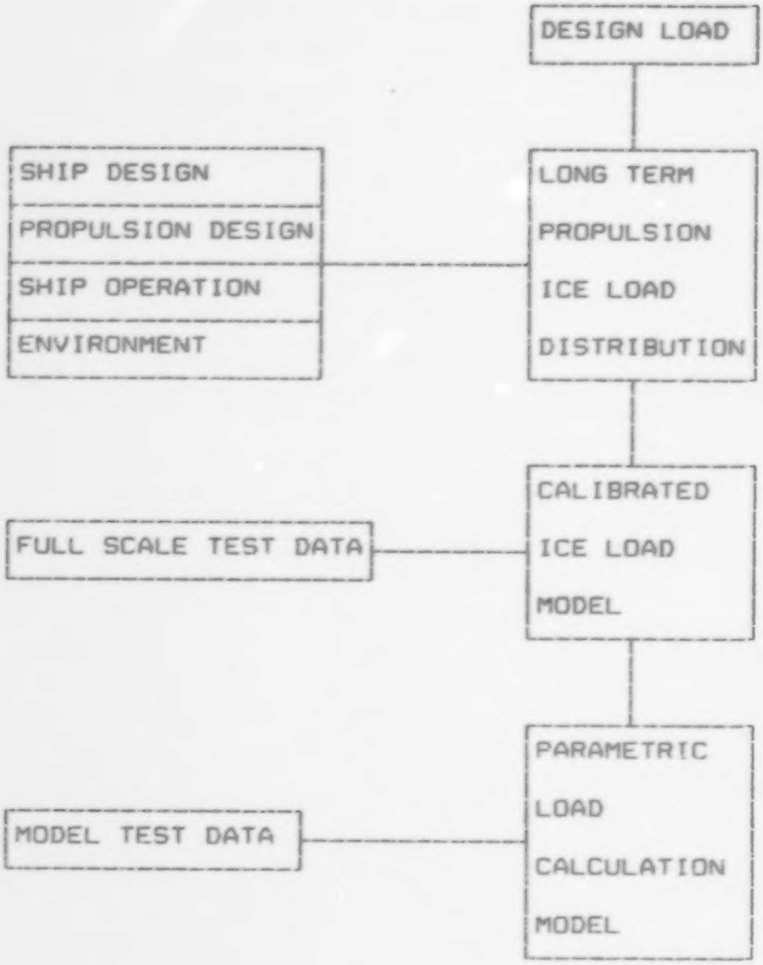

DESIGN LOAD
SHIP DESIGN
PROPULSION DESIGN
SHIP OPERATION
ENVIRONMENT
LONG TERM PROPULSION ICE LOAD DISTRIBUTION
FULL SCALE TEST DATA
CALIBRATED ICE LOAD MODEL
MODEL TEST DATA
PARAMETRIC LOAD CALCULATION MODEL

FIGURE 5.2
DESIGN LOAD CONCEPT
EXISTING SHIP
JARVSAAR

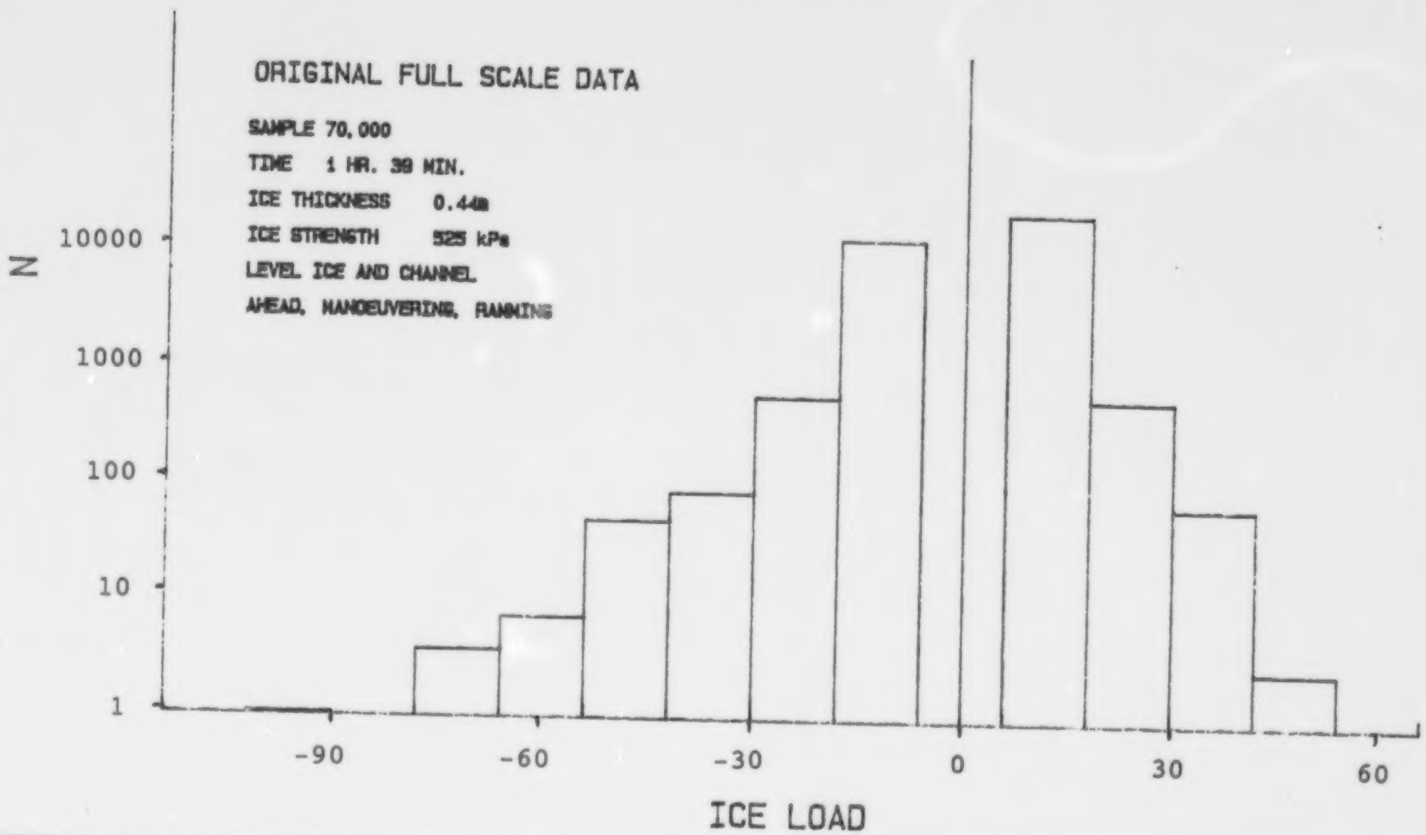
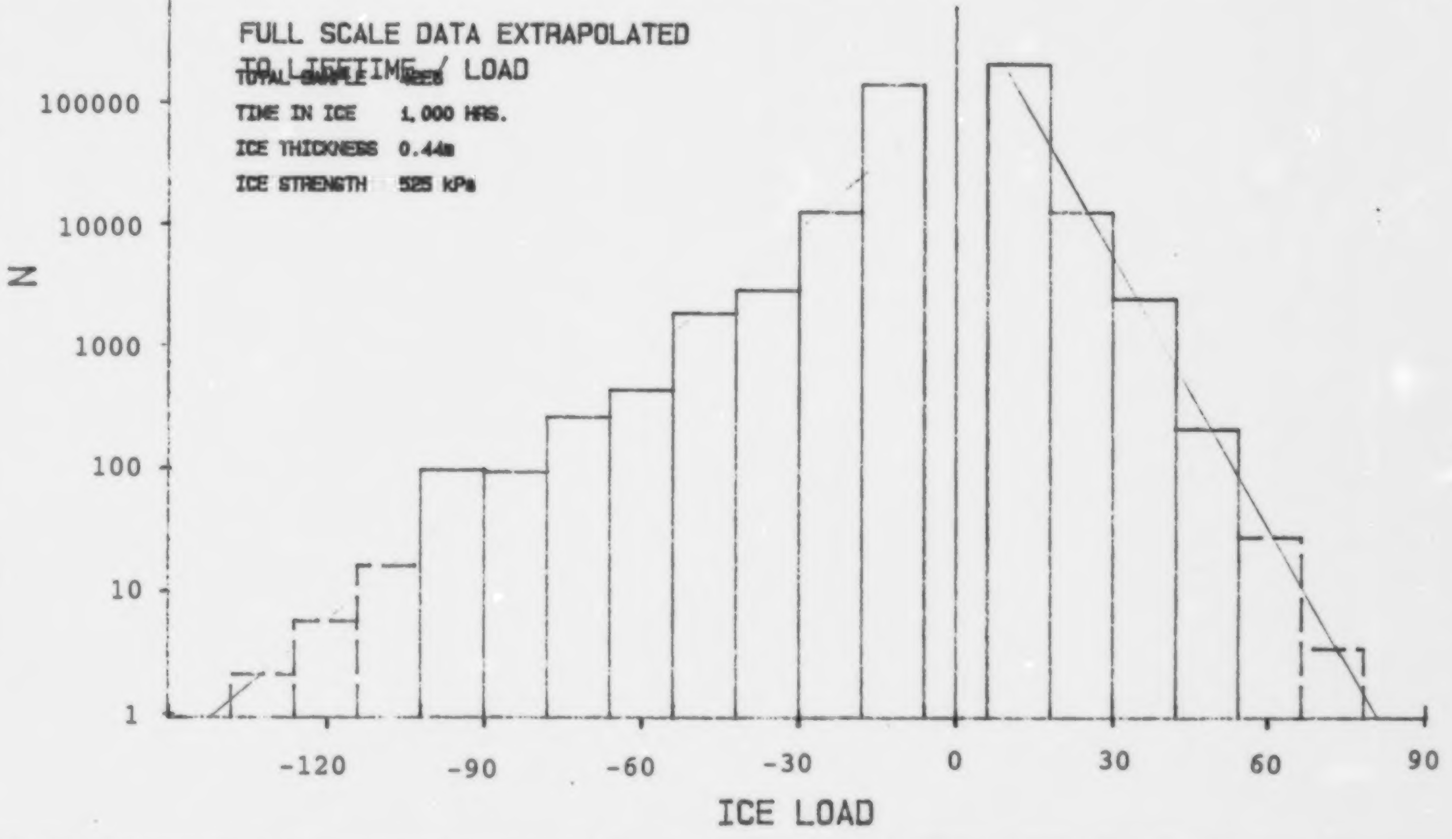


FIGURE 5.3
DESIGN LOAD CONCEPT
EXISTING SHIP
JARVSAAR



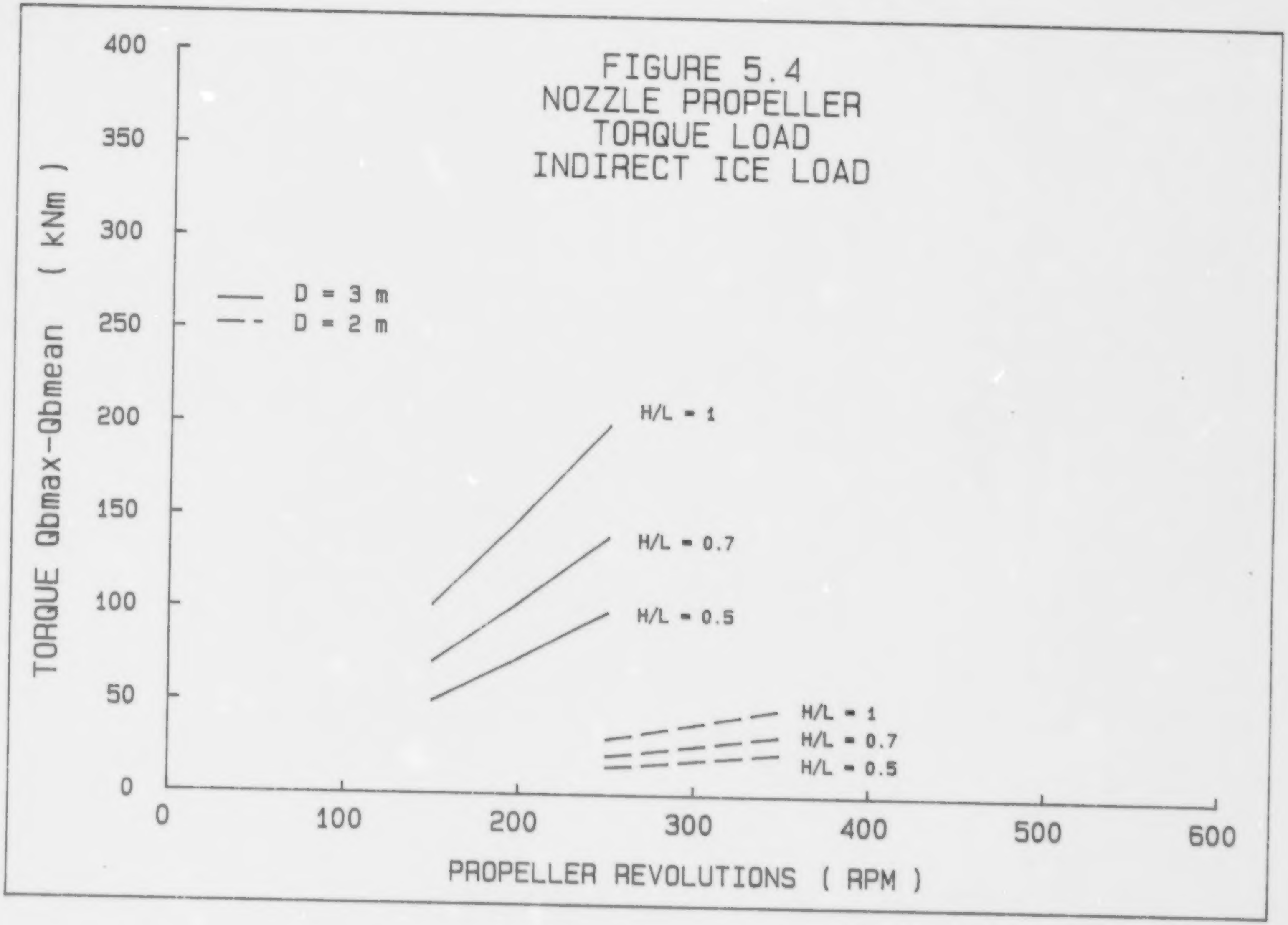


FIGURE 5.4
NOZZLE PROPELLER
TORQUE LOAD
INDIRECT ICE LOAD

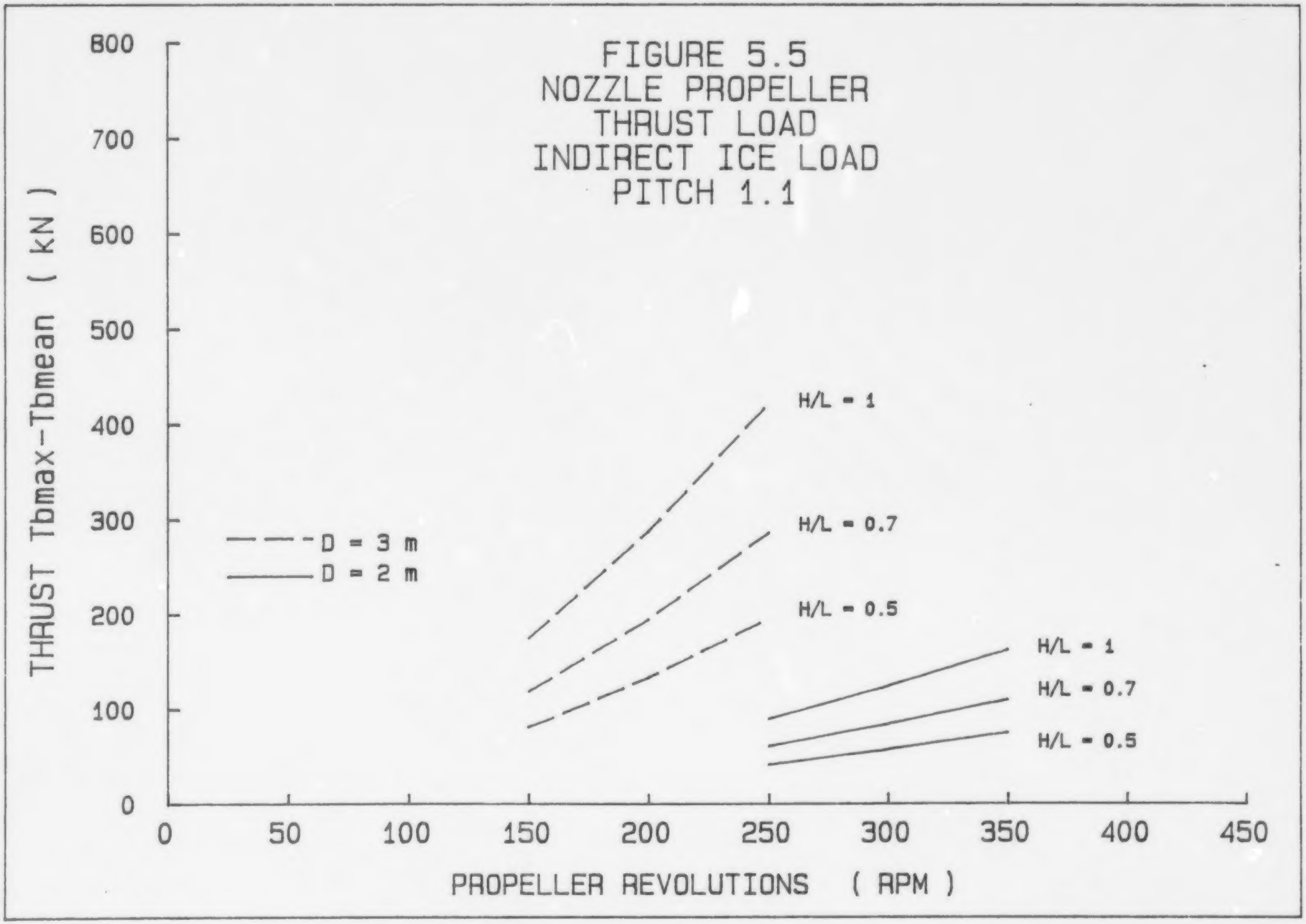


FIGURE 5.5
NOZZLE PROPELLER
THRUST LOAD
INDIRECT ICE LOAD
PITCH 1.1

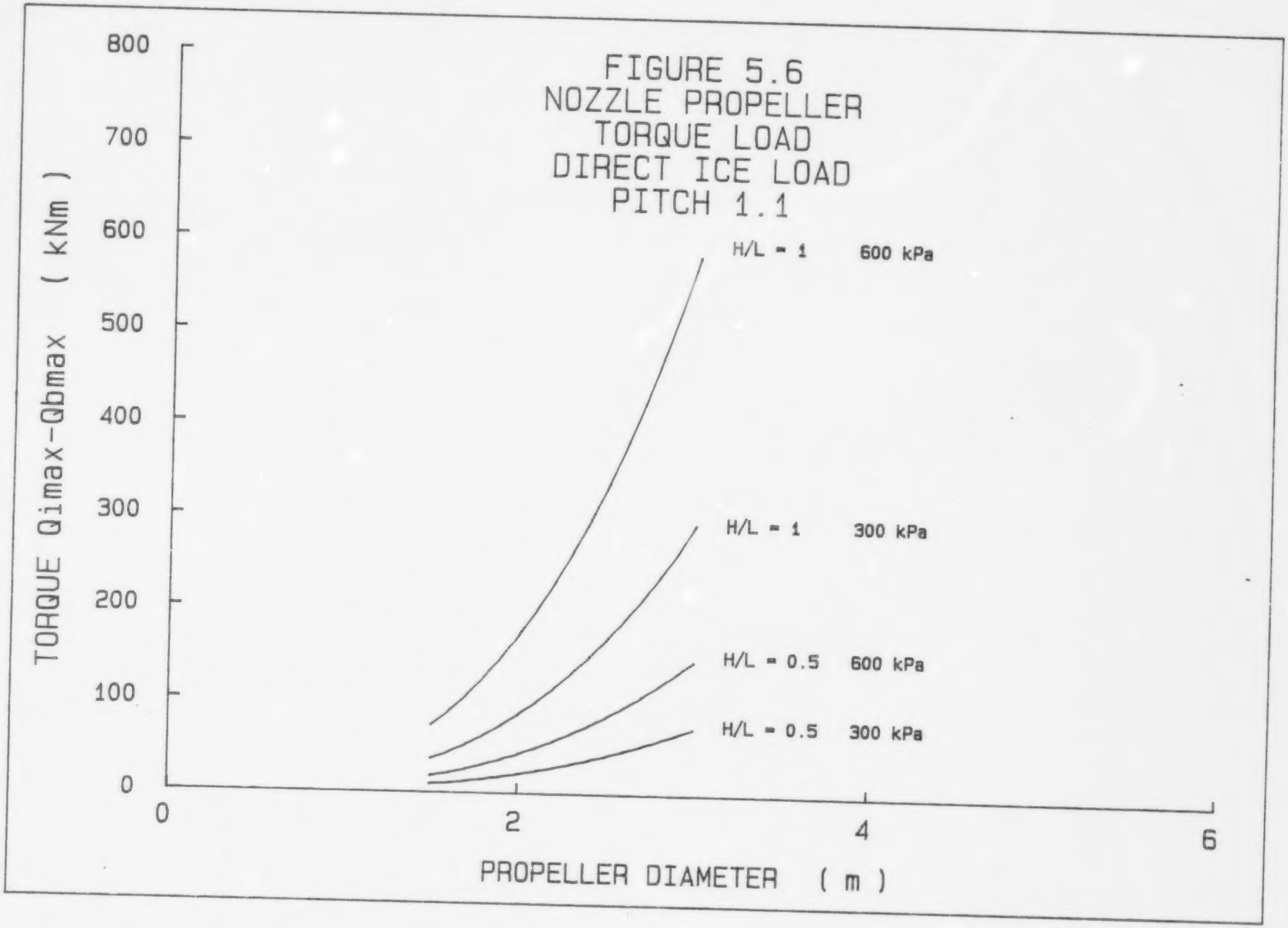


FIGURE 5.6
NOZZLE PROPELLER
TORQUE LOAD
DIRECT ICE LOAD
PITCH 1.1

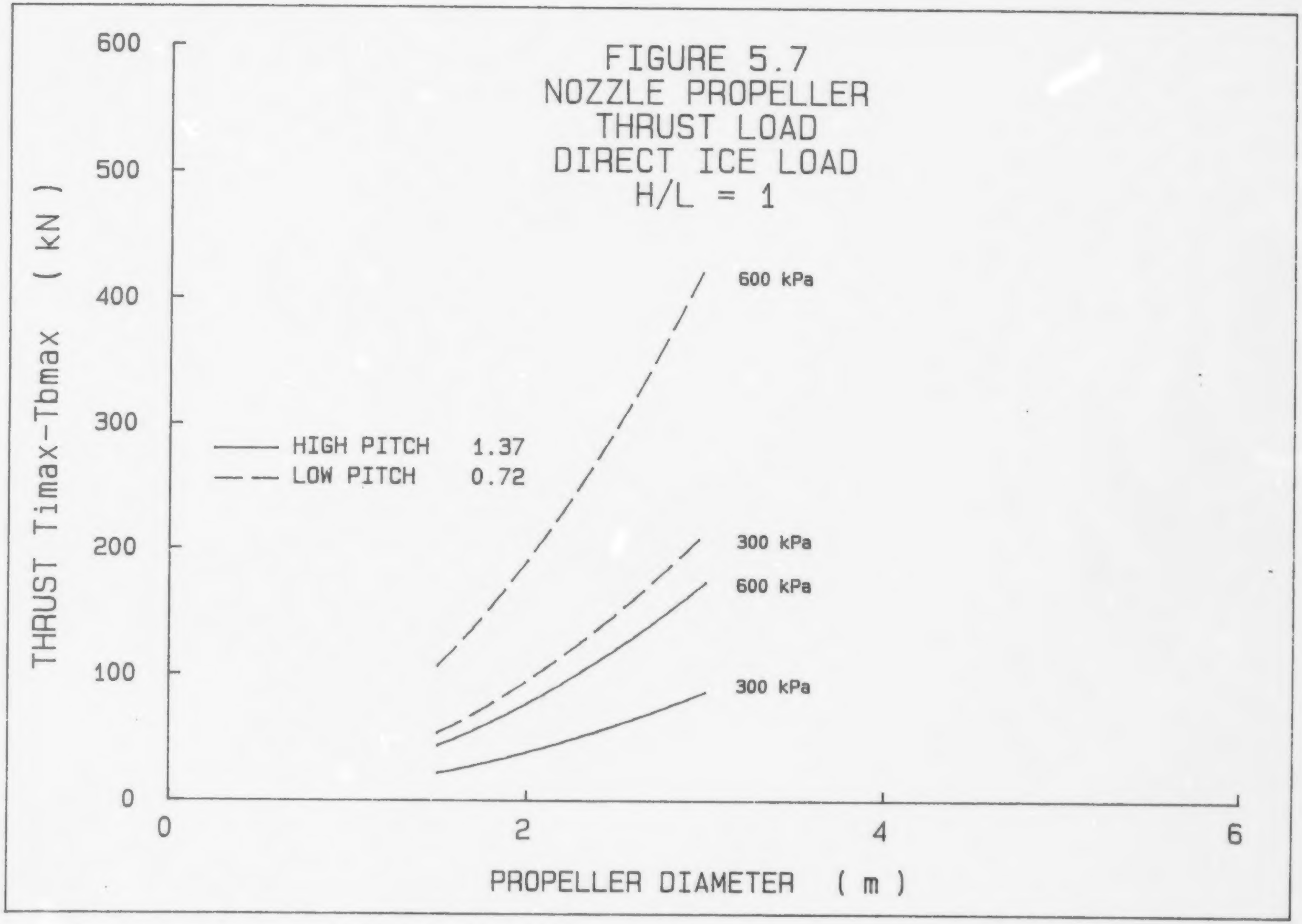


FIGURE 5.7
NOZZLE PROPELLER
THRUST LOAD
DIRECT ICE LOAD
H/L = 1

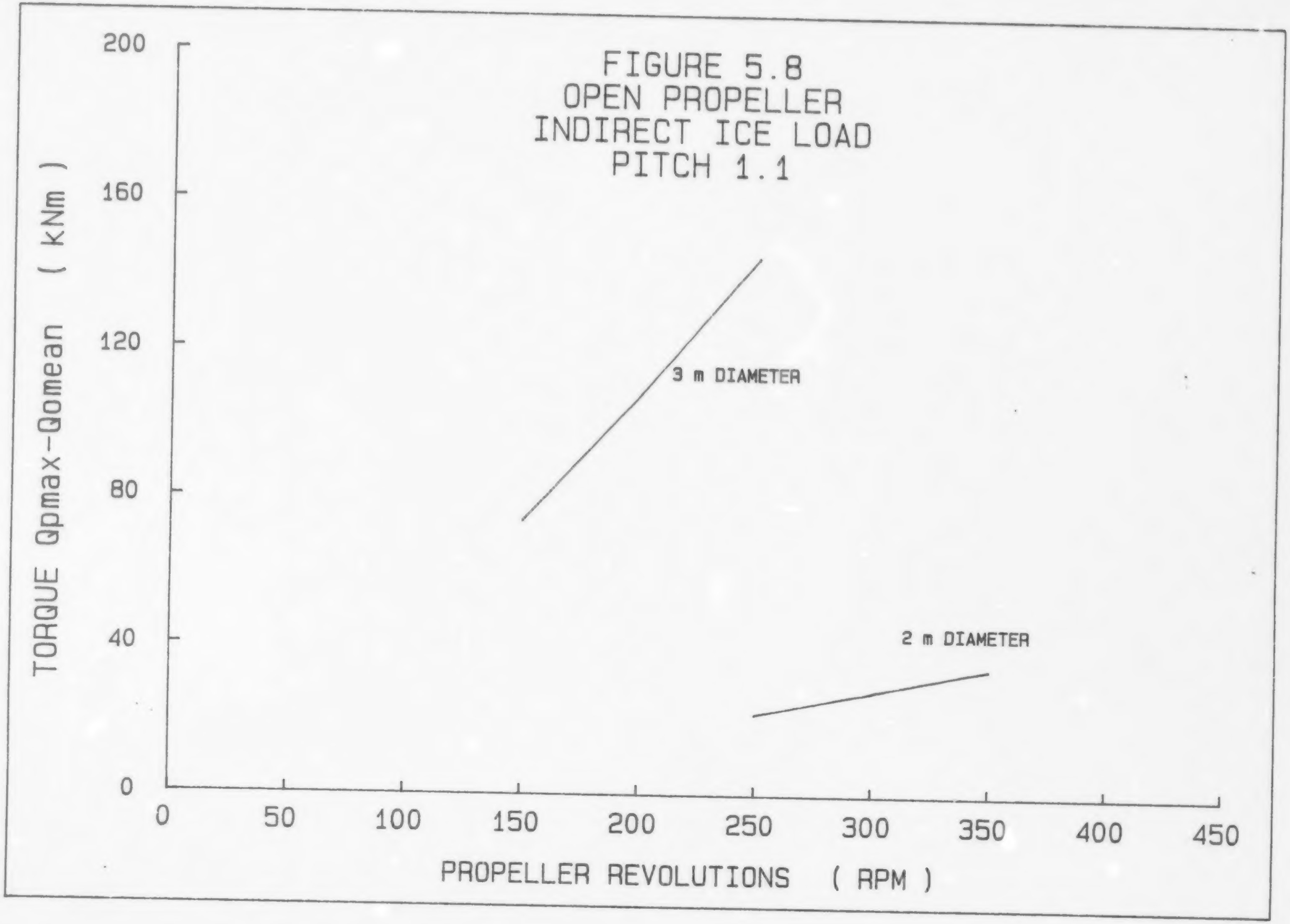


FIGURE 5.8
OPEN PROPELLER
INDIRECT ICE LOAD
PITCH 1.1

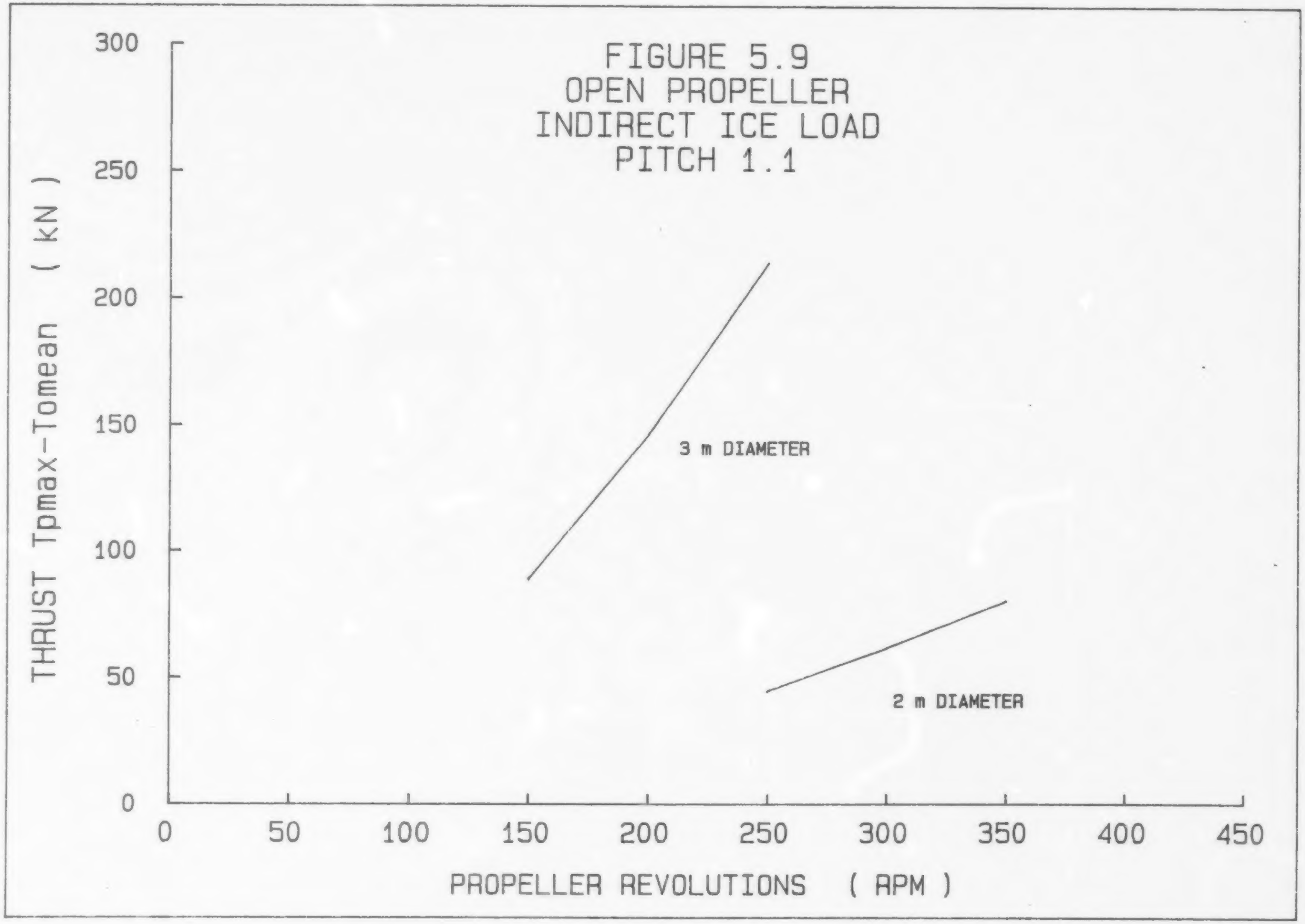


FIGURE 5.9
OPEN PROPELLER
INDIRECT ICE LOAD
PITCH 1.1

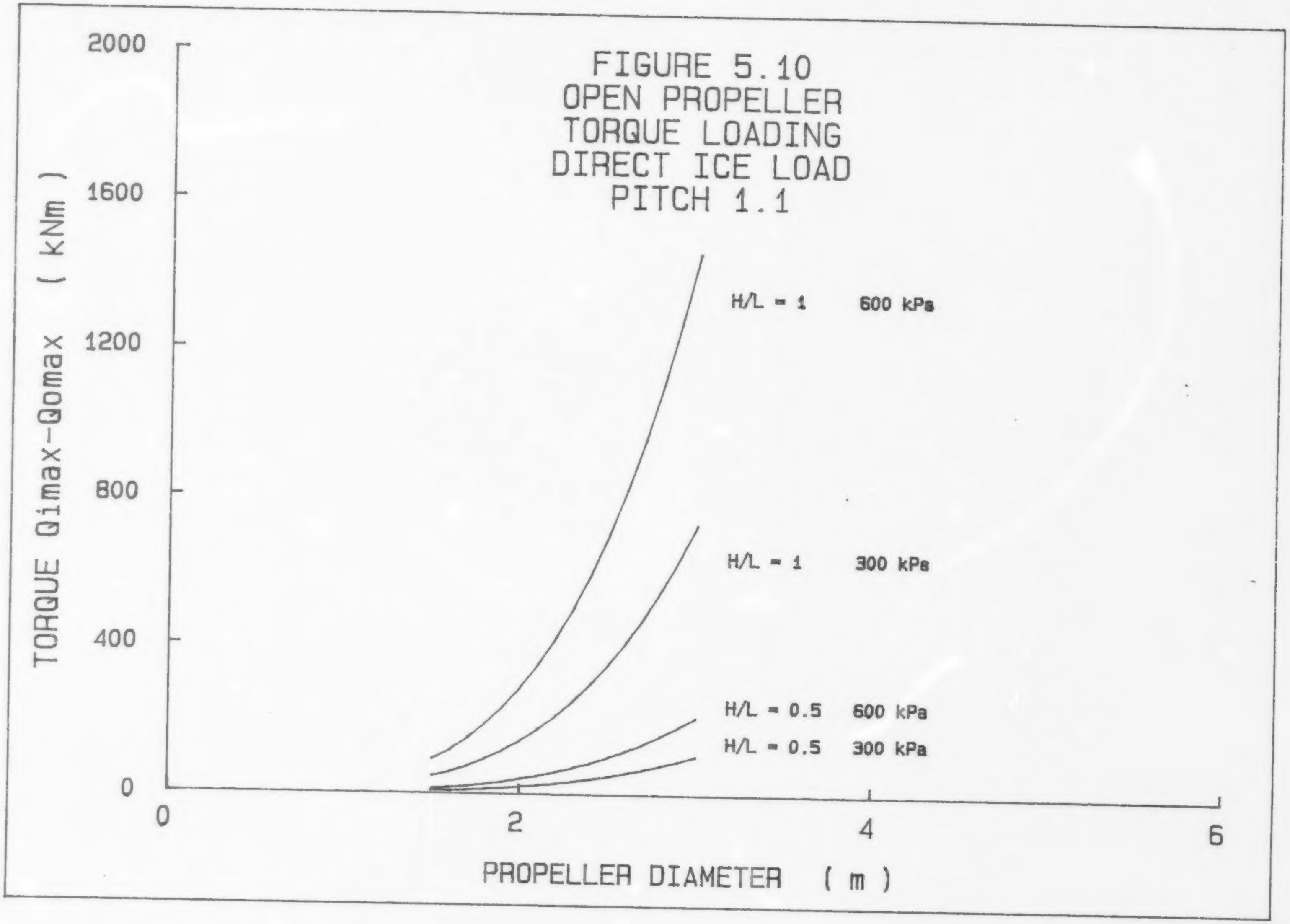


FIGURE 5.10
OPEN PROPELLER
TORQUE LOADING
DIRECT ICE LOAD
PITCH 1.1

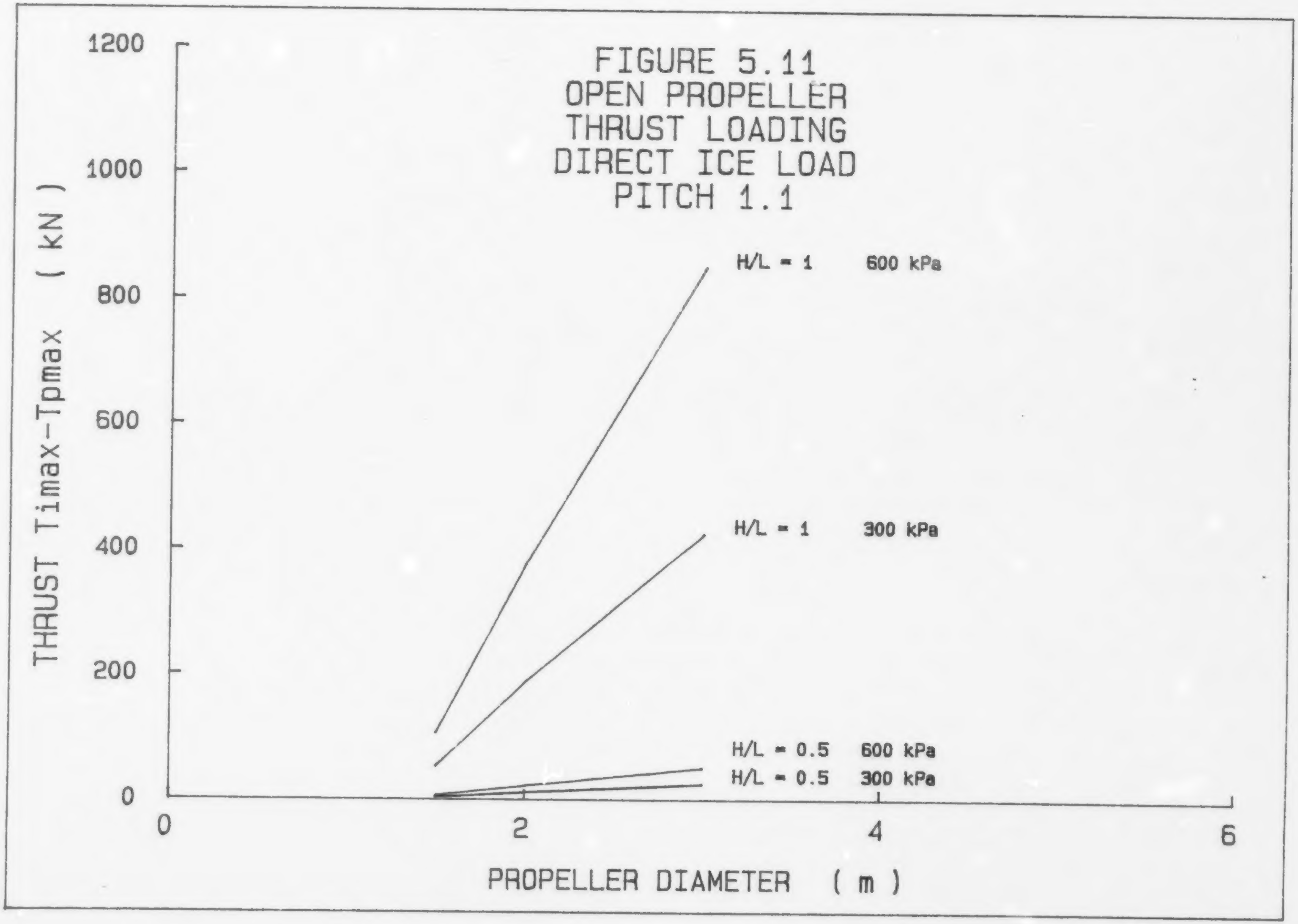


FIGURE 5.11
OPEN PROPELLER
THRUST LOADING
DIRECT ICE LOAD
PITCH 1.1

6. CONCLUSIONS

The overall conclusion from this project is that the process of systematically model testing open and ducted propellers in model ice in order to establish the interaction phenomena and loading levels worked extremely well. There is now a clear picture of the key phenomena and parameter influences for ice loads on open and ducted propellers, as well as equations for torque and thrust loading on full scale propellers. These influences have been established and calibrated for propellers of up to 2 to 3 meters in diameter. There is good confidence that these findings will hold for larger diameter propellers, but additional verification with full scale data for larger propellers is required.

Specific conclusions are:

1. Ice model tests worked very satisfactorily in simulating the phenomena and loading of both open and ducted propellers. Correlation between model and full scale tests was good in those cases where a reliable comparison was possible (Jarvsaar).

2. Separating the loading caused by ice into the indirect component of ice induced hydrodynamic load and the direct contact ice load worked very well and clearly showed how these two components are influenced differently by the parameters of ice properties and propulsion system design.

3. Key parameters influencing all direct ice propulsion loading were:

   - Ice thickness
   - Propeller Diameter
   - Ice Strength (expressed as flexural strength)

   Other parameters had either no clear influence or a minor influence relative to those of the above key parameters.

4. Key parameters influencing all indirect ice loading were:

   - Propeller diameter
   - Propeller revolutions
   - Ice thickness

   Other parameters had either no clear influence or a minor influence relative to those of the above key parameters.

5. The total ice load for single block interaction is higher for the open propeller than for the nozzle propeller. The open propeller load increases much faster with increasing ice thickness than the nozzle propeller load.

6. Nozzle propeller load is considerably increased as a consequence of feeding a continuous stream of ice blocks into the propeller, whereas the open propeller load increases very little. This indicates the importance of accounting for potential multiple block interactions for the nozzle propeller when designing for ice loads.

7. The direct thrust ice load was influenced considerably by pitch, the load increasing with decreasing pitch.

8. The influence of ice thickness and propeller size appear to be stronger for the open propeller than for the nozzle propeller. The influence of RPM on ice induced hydrodynamic load is similar for both open and nozzle propeller.

9. The loads given in this report are related specifically to the size, strength and frequency of ice blocks interacting with the propulsion system. In order to determine design loads for any particular vessel, the influence of the vessel's design and operational profile upon ice entering the propulsion system must additionally be determined.

7. RECOMMENDATIONS

The directly calculated propulsion loads presented in this report are deterministic and not alone usable as design loads. However, the load formulae for torque and thrust for open and ducted propellers may be used directly to extrapolate full scale ship propulsion data in one defined environment to another given environment. Additionally, the formulae may be used in the ship design process in order to assess the qualitative effect of both propulsion system design parameters and the operating environment upon propulsion system loading and hence design.

The influence of some parameters on propulsion and ice interaction loading remains to be established. Due to the excellent success of this model test series, it is recommended that a second model test series be performed in order to complete the parameter range. The most important of these parameters are:

- low and close to zero pitch
- astern mode of operation
- influence of nozzle as a load limiter
- influence of rudder
- higher and lower revolutions of propeller
- changing direction of operation
- proximity of hull

It is also recommended that a simple method be established to determine the influence of the key design parameters of a ship and its propulsion system upon the level of ice interaction. Basic parameters such as ship draft, propeller submersion, ship length and propulsion system protection should be considered. Additionally, the influence of the vessel's operational profile on ice interaction should be determined. For example, a commercial vessel designed for continuous transit through ice might be expected to experience a lower level of interaction than a multi-purpose icebreaker designed for aggressive operation, including extensive manoeuvring, in ice. The influence of ship design and operation parameters upon ice interaction frequency and magnitude can be investigated through a combination of full scale observations and measurements coupled with a specially planned model test program to fill in the lack of parametric variation in full scale.

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April 1990

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Un sommaire en français de ce rapport est inclus avant la Table des matières.

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16. Abstract

This project has systematically evaluated the influence of many parameters on the ice loading of propulsion systems. This is done by the use of model test series in an ice model basin. Both Open and Ducted propellers were studied.

The influence of the ice thickness, ice strength, ice block size, amount of ice fed to propeller, propeller revolutions, propeller pitch and vessel speed were established.

Separation of components of ice load was introduced. The three components are: basic hydrodynamic load in the absence of ice, ice-induced hydrodynamic load (or change of basic hydrodynamic load due to the presence of ice) and direct ice contact load.

Model test results were correlated with full-scale data of Jarvsaar and Robert Lemeur.

Ice load formulas were given for a range of propeller ice condition combinations.

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16. Résumé

Le présent projet avait pour but d'évaluer de façon méthodique l'influence de divers paramètres sur la sollicitation des systèmes de propulsion dans les glaces. Cette évaluation s'est faite au moyen d'essais sur modèles réduits d'hélices protégées par une tuyère et d'hélices non protégées.

Les essais ont permis de déterminer l'importance des facteurs suivants : épaisseur et résistance de la glace, dimensions du bloc, quantité de glace en contact avec l'hélice, pas de l'hélice, régime du système propulsif et vitesse d'avancement dans la glace.

Trois composantes de la charge globale exercée par les glaces ont été définies, soit : la charge hydrodynamique en l'absence de glace, la charge hydrodynamique en présence de glace et la charge directe au contact de la glace.

Les résultats des essais sur modèles réduits ont été comparés à ceux d'essais en mer avec les navires Jarvsaar et Robert-Lemeur.

Des équations de prévision de la performance de systèmes de propulsion ont été mises au point pour une plage donnée de paramètres de conception de systèmes propulsifs, de caractéristiques mécaniques des glaces et de conditions d'exploitation.

17. Mots clés
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1. INTRODUCTION

1.1. General

This document reports the model tests performed at IMD ice model basin January 26 - February 3, 1989. These were propulsion ice interaction tests with a specifically developed custom designed test vessel. The tests were a part of a project to Transportation Development Centre, to which project report this is APPENDIX A.

1.2. Objectives of tests

The objectives were twofold:

- develop an understanding of the underlaying phenomena of ice loading of open and nozzled propellers
- measure and present the parametric dependency of loading of open and nozzled propulsion on a wide range of parameters in ice loading

This model test series is performed to give two types of data for development and calibration of ice load calculation models for open and nozzled propeller. Firstly the interaction phenomenon will be determined associated with various types of propulsion ice interaction. Secondly the influence of key parameters will be determined on the peak ice loads and average ice loads over longer periods of time.

This project covers a wide selection of key parameters in order to have a genuinely unique data set in the same model ice conditions with similar setup for all the tests. This includes both nozzled and open propellers with controllable pitch (or in model tests actually fixed pitch which can be varied between model tests). The load situations used are from light to the most severe which could be envisaged.

There had been in the past indications that the hydrodynamic component of the propeller load from the presence of ice without any direct contact with the propeller is an important fraction of the total load when ice interacts with the propeller. This issue is addressed in the project by tests which simulate ice interactions with no actual ice contact with the propeller.

The results from these model tests will in this project in an analytical phase be used for both input in terms of the physical phenomena modeled as well as for semi empirical calibration of the models and in particular the influence of the many parameters tested.

1.3. General Approach

A vessel is built to test and measure a wide range of ice propeller interactions and response parameters in order to comprehensively collect the understanding and data on the key factors influencing the loading of open and nozzled propellers in ice.

The recordings cover all those parameters which are considered to have potential primary importance to the interaction. The visual recordings are done in such a way that the approximate dynamics and rate of progress of various sizes of ice floes can be analyzed, as well a to give a geometrically definable indication of likely contact between ice and the propeller. The data-aquisition is collecting data on the response of a propeller blade, on the shaft including its bending and the nozzle.

Test plan is such that a very wide range of test interactions is covered. The interaction caused by single ice blocks as well as a continuous feeding of a large number of ice blocks, called level ice in these tests, in a continuous fashion is covered, likewise the blockage of a nozzle is introduced, and in the open propeller case a hydrodynamic influence study with "ice" that is moving very close to the propeller but not touching it, this is a premilled ice case.

The modeling of the ice material is performed using IMD:s EGAD ice. The properties of model ice in general are not defined in all those respects which may have a major influence on the loads caused by the model ice on the propeller.
The approach in this project is to use this model ice as is, but to document, for the first time in IMD history the strength, elastic as well residual strength properties of this model ice material. This is believed to give the best possible data base today for the purposes of the project. It is considered that the rapid loading of ice by a rotating propeller in comparison to the lower rate of loading of the model ice by ship hull reduces the magnitude of the problems with the properties of model ice in comparison to field ice. The brittleness is easier maintained in model ice at fast loading rate and thus it is repeating the full scale phenomena better than tests at low loading rate of the model ice. For this project the interpretation of the model test data is performed at two stages. In this model test report the influence of the model ice properties, namely the flexural strength of the model ice is established. The true evaluation of the applicability of model ice and the test results from model ice will be performed in the connection of the scaling of the model test results to full scale data. The assessment of the quality of the model test results is made in that context in the main report of this project. The confidence in the successful applicability of the model test data is also combined with the facts that this project has the access to other data, in particular Robert Lemeur and Jarvsaar full scale data specifically collected on the propeller ice interaction.

The model tests are performed at normal pressure and thus the cavitation number of the propeller does not necessarily scale to any full scale data. The test results in this projects model tests are assessed within themselves. The assessment of the potential influence of the difference in the Reynolds number for cavitation number scaling is in the main report of the project.

1.4. Report Structure

This report reports the preparation of the specially built test equipment, the test program performed with it , the analysis of the test results as well as further interpretation of the test data and discusses the applicability of the test results for the analytical part of the project.

Chapter 2 describes the test vessel, criteria for its design and main features of it, as well as the measurement and data-aquisition equipment used.

Chapter 3 shows the test program performed and describes each type of test.

Chapter 4 describes the basic analyzing method for each of the test types and reports the main test results for signals including nozzle load, Blade Torque and Bearing Loads.

Initial data analysis for single tests as well as comparative analysis establishing key parameter influences on the loading of the propeller and shaft are presented in Chapter 4.

Chapter 5 describes data analysis as it applies to the main objectives of the project. The analysis of thrust and torque dependencies on key parameters is developed. Also the separation of components of the propulsion loading for these parameters is presented. The hydrodynamic loading in the absence of ice, the induced hydrodynamic loading in the presence of ice and the direct ice loading as a consequence from contact between propeller and ice are reported.

Chapter 6 discusses the influence of the key parameters on the components of thrust and torque loading. This includes separate assessment of such influences on the open and nozzled propeller as well as a comparison between the two.

Chapter 7 presents conclusions.

2. MODEL TESTING EQUIPMENT

2.1. Requirements

The requirements for the functioning and design of the model testing equipment are according to contract as follows:

- accommodates scale propeller 1:5 to 1:30 of any icebreaker propeller (20 to about 30 cm diameter)
- propeller, motor, nozzle and all measurement equipment to go into the vessel
- facilitates measurements of shaft thrust, torque, shaft bending, blade bending, blade spindle torque, nozzle longitudinal loads, two visual recordings (one through nozzle, one from front side)
- capability to be attached to the towing carriage at several positions over the ice model basin of IMD
- vessel breaks and displaces ice such that the ice pieces pass through the propeller - vessel can be run at variable drafts using controlled ice block sizes
- a moveable milling rig attachable to the propulsion vessel shall be constructed to tow pre-milled ice blocks past the open propeller
- a system to be provided to feed ice blocks into the propeller with reasonable accuracy in terms of position and orientation

The requirement for the propeller to be tested was that it is to be selected with IMD.

Essentially these requirements cover most every imaginable type of test with a propeller to measure and document ice propeller interaction.

2.2. Design of test vessel

The test vessel was designed by IMD. Input data for design was arrived at by Offshore Research Limited for practical functioning of the equipment. AKAC INC had charge of the fulfillment of the requirements for achieving the measurements and results required for the analytical parts of this project.

The vessel is designed from basic principles and tailor made for this project with the target in mind that it be as flexible as possible for performing this project as well as for the purposes of any further propeller ice interaction testing.

The design schematically is seen in Figure 2.1, to a sufficient accuracy for understanding the functioning of it and for being able to interpret the measurements. Detailed design drawings are held at IMD.

The propeller diameter is 0.28 m, the revolutions available for rotation are up to about 1800 RPM. The nozzle is a 37-type nozzle which is commonly used for icebreakers (all Beaufort Sea icebreakers for example). The propeller selected was a readily designed propeller intended originally for use on the Louis St. Laurent center propeller. The drawing of the propeller is shown in Figure 2.2.

The design values do very well fulfill the requirement for a 5 to 30 scale model. The smallest propeller that this models is 1.4 meters and the largest 8.4 meters. All the known icebreaker propellers with nozzles or open propellers are at least 1.9 meters and no more than 6.6 meters. In this project the reference full scale data comes from Jarvsaar and Robert Lemeur which have propeller diameters of 1.9 and 3 meters respectively.

All the requirements in 2.1 have been met by the design. There is excess flexibility in the current design to vary operational parameters with modifications to equipment far beyond that required for this project according to original contractual propulsion vessel requirements. There are in the current equipment for this project two more adjustable components in the vessel than originally thought to be required. There is a plexi-glass plane horizontally in the front of the propeller which can be adjusted freely to any vertical position independent of the propeller from about the top level of the propeller hub to about the top of the propeller. This plane is adjusted to control the vertical position of feeding the ice into the propeller. Also there is another independently adjustable horizontal plexi-plane above the propeller for the open propeller which can be vertically set at steps to simulate various clearances between the hull and the propeller. This plate also eliminates suction of air from the surface.

These extra features were built during the project to allow better current and future use of the vessel, simulating a wider range of variation of design parameters influencing ice entrance to the propeller and ice wedging between the hull and propeller when milling ice.

2.3. Measurement equipment

The following signals from the vessel are available for data-aquisition system on the test carriage for this test:

- shaft thrust
- shaft torque
- shaft bending (horizontal and vertical)
- blade bending
- blade spindle torque
- longitudinal force on nozzle (2 off, top/bottom)
- RPM

Figure 2.1 show the locations of the gauges relative to the components of the propulsion system.

All of the driving system and measurement devices were tailor made for this project with the exception of the dynamometer. Photographs showing the test equipment are in Figures 2.3 - 2.4.

The video equipment used was IMD standard video cameras plus a black and white underwater video. The light used for clear view of the propeller ice interaction was stroboscopic light. The frequency was matched with set blade frequency at each rate of propeller rotation. Thus it was possible to get a frozen picture of the interaction at each blade. The camera setup is schematically shown in Figure 2.1 and can also be seen in Figure 2.3.

2.4. Data-aquisition system

The data aquisition was performed using IMD standard system. The data was collected digitally at a frequency of 50 Hz and as a backup onto an analog tape. Selected data was re-digitized at a frequency of 200 Hz, from the back up tape.

3. TEST PROGRAM

3.1. General

The test program is built in such a way that all the important ice interactions will be modeled and the variation in test parameters is as wide as considered to be feasible within reason. The list of test types is a shown below:

- basic hydrodynamic tests
- nozzle blockage tests
- premilled tests
- single block tests
- level ice tests

The actual test parameters varied is as listed below:

- RPM (3 levels)
- vessel speed (bollard + 2 levels)
- ice thickness 2 levels (plus thicker blocks)
- ice strength (continuous variation)
- ice block size (3 levels)
- amount of blocks (3 levels, single, limited, unlimited)
- propeller pitch (2 levels)
- blockage ratio (2 levels)
- premilled depth (2 levels)
- nozzle/open

The total number of combinations is nearly twice as much as original contract included. This was practically arrived at in the course of the practical preparation of the tests as well as a better definition of the most important tests and variation of parameters for the analytical phase of this project. This is in some areas then compensated by reducing the levels of variation of a particular parameter or the number of combinations of parameters. The total scope is kept at the maximum feasible amount of testing that can be performed in the model basin in a day. This is mainly dictated by the degradation of the properties of the ice with time as well as the practical time it takes to perform the tests.

For the purposes of model testing no particular scale factor is necessary to determine. The approach selected was to vary the scale factor determining parameters on a wide range. For practical purposes scale range of 7 - 30 is considered feasible based on these tests. This will allow interpretation of test results for virtually any icebreaker. The ice strength was kept at 60 - 15 kPa of flexural strength, which corresponds to anywhere from 200 kPa to over 1 MPa in full scale depending on scale selection. The rotational speed of the shaft was determined based on the feasibility of the video recording. The video recording takes place at 30 frames per second and the rotational speed was set at 7.5 RPS (which has the blade frequency of 30 /second. The lower end of the rotational speed range was set at 1/2 that (3.7 RPS), which gives only a small fraction of the power at the higher revolutions. There was an intermediate shaft speed at 5.6 RPS used as well.

The vessel speed was set to bollard, 0.2 and 1.0 meters per second. These correspond to the lowest full scale ship speed, beyond bollard of about 0.6 m/s and to the highest of about 5.5 m/s.

As an example this propeller can be a 17th scale model of the Kalvik propeller with ice thicknesses of 0.85 and 1.7 m.

3.2. Description of tests

3.2.1. Individual block tests

These tests were performed in order to establish the systematic influence of ice thickness and ice block areal size on the ice loading of the blades and shaft, as well as that of the ice strength. The selection of ice block sizes was set at the thicknesses 50 and 100 mm which were basic ice sheet thicknesses to areal sizes of 100 x 100 mm 200 x 200 mm and 400 x 400 mm. The smallest of these block sizes clearly fitted through the nozzle, the medium one could fit provided it is in favorable orientation and the largest one of the blocks would need global breakage before fitting through the nozzle. For the open propeller the same ice block sizes were kept in order to arrive at a comparison of the influence of the nozzle in the case of identical ice block sizes. Additionally there were two sizes of 200 mm thick blocks fed manually to the propellers. Their sizes were 200 x 200 mm and 400 x 400 mm. These blocks represented the close to infinite size block, which does not globally fail. There a comparison between the open and the nozzle propeller is arrived at.

The parameters varied in these tests were:

- RPM
- vessel speed
- ice thickness
- ice block size
- ice strength
- pitch
- open/nozzled

These tests were performed by feeding individually ice blocks into the propulsion by getting the block under the plexi plate ahead of the propeller (see Fig 3.1), from where they got sucked into the propeller. The plexi plate was vertically movable adjusted based on experimentation during the first system test day in such a way that at various RPM values the three different ice block got sucked into the propeller in the upper half of the propeller. The orientation of the blocks was judged not needing control but rather it being better to allow some randomness in how the blocks actually entered the propeller. The test results are an actual proof of the validity of this approach. The variation in the results should not be large in terms of the energy that is absorbed when getting a determined size of ice block into the propeller. Also the variation of the highest peak torque or other load component should not be big.

It turned out that the in practice the smaller blocks raise faster to the surface and thus hit the propeller marginally higher than the larger blocks. However it also turned out that the larger blocks interact with the whole top half, or sometimes the whole area of the propeller, no matter where they initially enter the propeller. It is judged therefore that the manual feeding accuracy using the plexi plate as a vertical movement guide is satisfactory for the purposes of this project.

The tests were performed at bollard and higher speeds. The path of the ice blocks varies as a function of the vessel speed as well, thus the plexi plane ahead of the propeller needs adjusting for proper ice entrance into the propeller depending on the speed.

3.2.2. Level ice tests

The level ice tests were carried out to get a realistic situation in terms of feeding ice into the propeller more than just the single blocks. The influence of the larger amount of ice going into the propeller is thus established.

The parameters varied in these tests were:

- ice block size
- ice strength
- ice thickness
- amount of ice blocks
- vessel speed
- pitch
- RPM
- open/nozzled

The ice block size was controlled by the angle of the breaking plane (see Figure 3.1). Closer to vertical the plane will break smaller ice blocks and at shallow angles larger blocks.

The ice strength varies automatically with time. The ice strength reduces with time, and the actual strength is determined by using regular measurements of it in the course of the test day. The ice thickness is as selected. For level ice 50 mm and 100 mm ice sheets were used.

The amount of ice getting into the propeller was a variable initially not anticipated to be as important as it turned out to be. It turned out that most of the ice that is broken by the breaking plane will be sucked through the propeller. Thus the width of the cut was adjusted by the amount of sideways transfer of the carriage from one test to another. The cut widths were adapted to, 20 cm and 40 cm.

The test were performed by running about 30 meters as a test run at a set RPM and vessel speed as well as the other set parameter values.

3.2.3. Basic Hydrodynamic tests

In order to determine the influence of ice on the loading of the propulsion the basic comparison level is always the hydrodynamic load level. Thus a comparative set of hydrodynamic performance data is required to have the base line. The delivered thrust and loadings of blade and shaft line were measured.

The propeller performance was measured for the full matrix of RPM, pitch speed variations applied in the ice interaction tests for both the open and nozzled propeller.

3.2.4. Blockage tests

The purpose of the blockage tests is to closely repeat and existing test of blockage in a cavitation tunnel. This is in order to establish how representative the hydrodynamic influences from the ice model basin tests are in a blockage situation. In the ice model basin it is not possible to scale the cavitation and thus this comparison test shows the importance of modeling the cavitation properly.

The selected test for repeating was a partial blockage test covering the entrance of the nozzle by a straight plate as shown in Figure 3.2.

The blockage tests were performed in bollard condition only, varying the RPM and the pitch for a nozzled propeller.

3.2.6. Premilled tests

This test is also a hydrodynamic influence test. It is established how much it loads the propeller to have a restricted water flow into the propeller by a large block which simulates a milled ice block. The block is run as close to the propeller blades as possible without it touching the blades, as shown in Figure 3.3.

The hydrodynamic influence of premilled blocks is measured for two different milling depths in bollard condition for the open propeller varying RPM and pitch.

3.3. List of tests

A full list of tests is in Table 3.1. All the levels of the parameters relevant to each tests are shown in this table, as well a the combinations of parameters actually tested.

4. NOZZLE LOAD, BLADE TORQUE AND BEARING LOAD DATA ANALYSIS

4.1 Data-Analysis, General

The results of the tests are analyzed individually for each test in a statistical manner. The average , minimum , maximum as well as standard deviation of each of the signals is presented for the duration of the ice interaction event/events for each test segment. Video is reviewed in order to be able to establish the type of interaction, quantify it and to establish key parameters for the interaction between propeller and ice.

The results are further analyzed for two purposes.

Firstly the highest priority for this project is to arrive at a supporting documentation for the mathematical model development for design loads on propulsion . This includes a thorough analysis of the thrust and torque loading. The remaining parameters are analyzed as required to support the development of the thrust and torque models.

Secondly there are several parameters the influence of which is not required to be analyzed extensively for the current scope of mathematical model and design load developments. The influence of these is established straightforward as they were measured in the model tests. These parameters are analyzed in this project to an extent to establishing the basic dependencies between the input parameters and the loading.

Here the results are presented first for the basic dependencies between the input parameters and the loading in different types of tests for the nozzle loads, blade torque loads and bearing loads. This is presented in this chapter (Chapter 4).

Thrust and torque are analyzed in Chapter 5 as it pertains to the development of the design load scenarios, and to the separation of the hydrodynamic influence of ice from the direct influence of ice on propulsion loading.

General comments of analysis of ice properties and use of ice flexural strength as the index strength for the interpretation is given in Subsection 4.2.1.

The test types reported here are:

- ice free tests
- ice block feeding
- level ice tests
- blockage tests of nozzle propeller
- premilled tests of open propeller

All test data is listed in a master list, Table 4.1. In this Table the key parameters identifying the data have been shown. For each of the events, which are represented each by one line in Table 4.1, there is a statistical data analysis performed for each of the measured signals. The signals in the data traces have been, depending on the test setup :

- shaft torque
- shaft thrust
- propeller RPM
- Carriage Speed
- X-load, Nozzle Top
- X-load, Nozzle Bottom
- Vertical Shaft bending Force
- Horizontal Shaft Bending Force

For each test, on the top of these the pitch setting was noted as well as the presence of the nozzle, which was varied between test days. For special tests such as blockage of nozzle and premilled piece test for open propeller a separate note is made of the percentage of disk area covered by the blocking plate or the premilled sector. The recording of the ice data contained IMD standard measurements as well as some measurements to establish the residual strength and elastic properties of the level ice. The standard measurements for each test sequence include flexural strength and thickness measurements before and/or after each test sequence to get an actual ice strength for each test. As required for the objectives of this project for selected individual tests the following was also noted or analyzed:

- size of block (thickness * length * width)
- orientation of block (for the most severe loads only)
- notes on any special observations (blockage, splitting of blocks, differences in breakage, unexpected movements etc.)

The way that the ice properties have been handled in this project in terms of their influence on propulsion loading is through direct full scale model scale result comparison. This gives empirical correction factors scaling from the model scale to full scale. The actual mode of ice failure can vary in propeller ice interaction from flexural breakage of ice for example when ice hits the nozzle, to shearing and crushing when ice hits the leading edge of the propeller blade or just straight crushing when the ice hits the flat surface of the propeller blade. There is no established way of handling these different breaking components in a propeller ice interaction, to establish scaling laws. Development of such eventually can be the target but for this project it is considered to be the appropriate scope to assess for the scaling of the loads whether the breaking energy difference between full scale and model has been an important contributor to the scaling factors established. The other aspect is the influence of potential change of phenomena between the model and full scale conditions. This is also assessed in each main load case and main result, where applicable.

The flexural strength of the ice has been used as the index for ice properties. This has been the only established ice property that IMD has used systematically for this purpose and the only one that systematically was measured throughout the tests.

Section 4 is structures to present nozzle load, blade torque, and bearing load each in its own sub-section. Nozzle loads are presented in Section 4.2, Blade Torque load in Section 4.3 and Bearing Load in Section 4.4. Section 4.5 summarizes the main results from all of the sections. The results are presented in graph form with observations included within the text. Each sub-section consists of two sets of graphs: the effects of RPS on the given load and the effects of velocity on the given load.

The tests chosen for analyzing the effects of RPS consisted of bollard, high pitch, both nozzled and open propellers, 100 mm thick ice, and all block sizes. These parameters were set to obtain the largest group of data without analyzing every possible combination of parameters. The results thus obtained show the general trends that should be expected.

4.1.1 Definitions and Terminology

It was found in analyzing the results that there existed a variation of hydrodynamic means of various loads . This variation effected the presentation of the loads since the magnitude of the ice induced load depended on its initial hydrodynamically loaded condition. Therefore to analyze the influence of ice on the loading, the hydrodynamic mean for each test point was subtracted from that test point. The term blocks-icefree was used to describe the adjusted data. Blocks refers to the data measured under conditions loaded by ice and icefree refers to the hydrodynamic mean of load without the presence of ice.

The disadvantage of displaying only the shift of measured parameter under loaded condition is that the magnitude of the actual load is not displayed. The hydrodynamic loads have thus been included as a separate set of graphs along with the blocks-icefree results so that the entire loading can be determined. The entire load present is the sum of the hydrodynamic mean and its corresponding blocks-icefree load.

In the observations presented with the graphed results the term increased is used often. In all cases its use refers to the magnitude of a given load. Thus if a load is negative and is seen to become more negative as a parameter is changed its magnitude is increasing and the term the load increased is used.

In most cases the maximum load is positive and the minimum load is negative. Thus if it is said that both the maximum and minimum load increase with some parameter it is meant that the maximum load becomes more positive and the minimum load becomes more negative.

4.1.2 Ice Strength

In this section the effect of ice strength was not analyzed. Therefore the data presented have various ice strengths. The range of ice strengths is presented with the results. It was found that the ice strength varied by no more than 10 kPa in any set of data. It is felt that such a small range has a negligible effect on the general trends of the data. This sections purpose is only to present the results in a clear manner and to point out any trends in the dependencies which can be observed.

4.2 Nozzle Load

Nozzle loads both at the top and bottom of the nozzle are analyzed separately and presented here. The positive direction of measurement is the direction of positive thrust. The maximum, the minimum and the average of the nozzle loads were determined from the data traces. A minimum nozzle load measurement corresponds to an ice impact on the nozzle and the maximum nozzle load measurement is a response to the impact; all tests were performed ahead, there are no impacts from the aft. The nozzle load results presented in this section are:

- maximum, minimum, and average top and bottom nozzle loads vs. RPS (blocks-icefree) for bollard, high pitch, 100 mm thick ice, and all block sizes and the corresponding maximum, minimum, and average top and bottom hydrodynamic nozzle loads vs. RPS

- maximum, minimum, and average top and bottom nozzle load vs. velocity (blocks-icefree) for bollard, high pitch, 100 mm thick ice, and all block sizes and the corresponding maximum, minimum, and average top and bottom hydrodynamic nozzle loads vs. velocity

- maximum, minimum, and average top and bottom nozzle loads for blockage at bollard, high pitch, and low pitch

- maximum, minimum, and average top and bottom nozzle loads vs. RPS and vs. velocity (blocks-icefree) for bollard, low pitch, 100 mm thick ice, 400 mm blocks

4.2.1 Nozzle Load vs. RPS

Hydrodynamic Loads:

The top and bottom hydrodynamic nozzle loads corresponding to the results given in this section are shown in Fig. 4.2.1. The variability of the hydrodynamic loads as mentioned in section 4.1.2 is apparent in this figure. However, within the same test sequence the results are very consistent. The scatter in the results is associated with creep in zero values of the loads from one test time to another. The increase in hydrodynamic load with RPS is larger for the bottom than the top nozzle load. This gives an indication of the relative magnitudes the top and the bottom gages measured of the load.

Blockage Loads:

The effect of flat plate blockage on nozzle load is shown in Fig. 4.2.2 for high pitch and in Fig. 4.2.3 for low pitch. The effects are:

- At low blockage the effect of increasing RPS is to increase the nozzle thrust and loads. At higher blockage the effect of RPS is to decrease the nozzle thrust and load.

- If the hydrodynamic loads presented in Fig. 4.2.1 are observed and compared to the loads in Fig. 4.2.2. it can be seen that as the percentage of blockage is increased the effect is to decrease the thrust and the nozzle load. At zero blockage (hydrodynamic) the effect of RPS is to increase the thrust on the nozzle. At 10 % blockage the increase in thrust is less, and at 30 % blockage the effect has become negative.

Block Loads:

Figure 4.2.4 shows the effects of RPS on top and bottom nozzle loads for three different block sizes. From the figure the observed trends are:

- the minimum and average nozzle loads increase in the negative direction with increasing RPS, which indicates drop of thrust, and also the minimum load is larger than the hydrodynamic nozzle load leading to an absolute change of direction of total nozzle loading from ahead, thrust advancing, to astern.

- the largest minimum nozzle loads are the impact loads from an ice block and it can be seen that the influence of RPS, being in bollard condition approximately directly linearly is reflected in the peak minimum loads. The impact speed being roughly directly proportional to the RPS, indicates thus that the impact load is directly linearly dependent on the impact speed.

- the maximum and average nozzle loads are similar in magnitude for both the top and bottom of the nozzle. This indicates that more impacts on the nozzle take place at the top half, because the balance of the loads has shifted up from the bottom load being higher in pure hydrodynamic loading to the two being close to equal.
- the minimum nozzle load is larger in magnitude for the top than for the bottom of the nozzle. This indicates the biggest impacts having taken place closer to the top of the nozzle than to the bottom.
- all nozzle loads increase in magnitude with increasing block size. This influence appears to be approximately linearly in proportion to the block length dimension.

Low Pitch:

The effects of low pitch is demonstrated in Fig. 4.2.5. Comparing this figure to Fig. 4.2.4 the effect of low pitch is a lower response in minimum nozzle load. This effectively means that the thrust on the nozzle is not affected as much by impacts for the low pitch case as for the high pitch case.

The nozzle load seems to be more than linearly increasing with the RPS. This indicates that at low RPS and pitch the impact speed of the ice block might not be quite as high as the directly indicated speed of water flow through the nozzle.

4.2.2 Nozzle Load vs. Velocity

Hydrodynamic Loads:

The top and bottom hydrodynamic nozzle loads with respect to velocity are shown in Fig. 4.2.6, for use as reference values to relate the ice induced loads to them.

Block Loads:

Figure 4.2.7 shows the effect of velocity on both the top and bottom nozzle loads for all three block sizes. The visible trends are:

- all nozzle loads appear to be unaffected by velocity. This suggests that the propeller suction has been more important in determining the impact speed of the ice blocks.

- top and bottom nozzle loads are similar in magnitude. This suggests again the shift of balance up of the loading of nozzle, or more ice impacts and interaction on the top half of the nozzle.

- all nozzle loads increase in magnitude with increasing block size in a similar fashion as in the bollard condition.

Low Pitch:

The effect of velocity on the nozzle load for low pitch is shown in Fig. 4.2.8. Comparing Fig. 4.2.8 to Fig. 4.2.7, the effect of low pitch is to only decrease the magnitude of the response. The nozzle loads are still not effected by velocity.

4.3 Blade Torque

The maximum, the minimum, and the average blade torque measurements are presented in this section. As before, the hydrodynamic means have been presented separately and then subtracted from the measured loads. The following blade torque results are included in this section:

- maximum, minimum, and average blade torque vs. RPS for bollard, high pitch, nozzled and open propellers, 100 mm thick ice, and all block sizes and the corresponding maximum, minimum, and average hydrodynamic blade torque vs. RPS

- maximum, minimum, and average blade torque vs. velocity for 7.5 RPS, high pitch, nozzled and open propellers, 100 mm thick ice, and all block sizes and the corresponding maximum, minimum, and average hydrodynamic blade torque vs. velocity

- maximum, minimum, and average blade torque for blockage, bollard, high and low pitch

4.3.1 Blade Torque vs. RPS

Hydrodynamic Loads:

The hydrodynamic blade torque, or spindle torque, as a function of RPS for both nozzled and open propellers is shown in Fig. 4.3.1. A remarkable difference exists between the blade torque responses for the ducted screw and the open screw. For the ducted screw the hydrodynamic blade torque decreases with increasing RPS but for the open screw the hydrodynamic blade torque increases with increasing RPS. This indicates a shift of the hydrodynamic centre of the pressure on the blade. For the nozzle the hydrodynamic centre is further forward and the spindle torque is in the direction of increasing pitch, whereas for open propeller the hydrodynamic center of pressure on the blade is behind the axis of pitch rotation.

Blockage:

The effect of blockage is shown in Fig. 4.3.2 and Fig. 4.3.3. Again there is an opposite effect between ducted and open propellers. The blade torque response is negative for ducted screw and positive for open screw. Further as the amount of blockage increases the magnitude of the response increases. No difference exists between low pitch and high pitch for blockage events.

Block Loads:

The variation of the blade torque from the hydrodynamic mean with respect to RPS is shown in Fig. 4.3.4 for both nozzled and open propellers and for all block sizes. The observable trends include:

- the magnitude of the blade torque increases in magnitude with increasing RPS for the nozzled propeller.
- the magnitude of the blade torque decreases with increasing RPS for the open propeller, an effect opposite to that for the nozzle propeller
- block size has no effect on the blade torque for the nozzled propeller but increases the magnitude of the blade torque for the open propeller with increasing block size.
- the maximum blade torque has a larger increase with RPS than the minimum blade torque for the open propeller, an opposite effect than that for the nozzle propeller
- the blade torque load average for both nozzled and open propellers remains close to its hydrodynamic value at all RPS

Low Pitch:

Fig. 4.3.5 shows the effect of RPS on the blade torque of a low pitch orientation.

4.3.2 Blade Torque vs. Velocity

Hydrodynamic Load:

The hydrodynamic blade torque as a function of velocity is shown in Fig. 4.3.6 for the corresponding loading cases presented in this section. From this figure it can be observed that the hydrodynamic blade torque is practically unaffected by velocity. Further the hydrodynamic blade torque for the nozzle propeller is negative while the hydrodynamic blade torque for the open propeller is positive. Once more there is opposing effects on blade torque for the nozzled and open propellers.

Block Loads:

The blade torque loads with respect to velocity are shown in Fig. 4.3.7 for both the nozzled and open propeller and all block sizes. The general trends are:

- the magnitude of the blade torque for both open and nozzle propellers is virtually unaffected by velocity. This indicates the impact speed between ice and propeller blade is a function of RPS rather than of speed of the vessel.

- the average blade torque response does not vary from the hydrodynamic mean for both the nozzled and open propellers

Low Pitch

The effect of velocity for low pitch is shown in Fig. 4.3.8 and has no effect on the blade torque.

4.4 Bearing Load

This section includes the following bearing load results:

- horizontal and vertical bearing load vs. RPS for bollard, high pitch, nozzled and open propellers, 100 mm thick, all block sizes and the corresponding maximum, minimum, and average hydrodynamic horizontal and vertical bearing load vs. RPS

- horizontal and vertical bearing load vs. velocity for 7.5 RPS, high, nozzled and open propellers, 100 mm thick, all block sizes and corresponding maximum, minimum, and average hydrodynamic horizontal and vertical bearing load vs. velocity

- horizontal and vertical bearing load for blockage, bollard, high and low pitch

- horizontal and vertical bearing load for low pitch vs. RPS and velocity

4.4.1 Horizontal an Vertical Bearing Load vs. RPS

Hydrodynamic Loads:

The hydrodynamic horizontal bearing loads are shown in Fig. 4.4.1 along with the hydrodynamic vertical bearing load as a function of RPS. For the horizontal bearing load the hydrodynamic appears to be unaffected by RPS and there is a small difference in magnitude between ducted and open propellers the maximum and minimum bearing loads being slightly higher for the ducted propeller.

Blockage:

The effect of flat plate blockage on horizontal and vertical bearing loads is shown in Fig. 4.4.2 and Fig. 4.4.3 for the ducted propeller and the effect of premilled for the open propeller in Fig. 4.4.4. The following main trends are noted:

- the horizontal bearing load is only marginally influenced by the blockage by a slight shift of the average towards the blocked side, the amplitude around the average staying about the same as in hydrodynamic non blocked situation.

- lower pitch is associated with lower amplitude of variation and slightly lower average bearing loads. The reduced amplitude can be associated with the longer distance between the blocking pate and the leading edge of the blade, as a consequence of pitch reduction.

- vertical bearing load variation between maximum and minimum increases as a function of the RPS.

- vertical bearing load average shifts with increasing RPS and also shifts much more than the horizontal bearing load. The blocking plate has been placed to block on side of the nozzle with a vertical edge in front of the propeller.

- premilled situation differs from the blocked in that the premilled piece had a horizontal edge of the block. The bearing loads both vertical and horizontal are only influenced in a minor way by the premilled situation.

Block Loads:

Figures 4.4.5 and 4.4.6 contains the effects of RPS on horizontal bearing load for bollard, high pitch, nozzled and open propellers, 100 mm thick ice of all block sizes. The observed trends are:

- block size appears to have small effect on the horizontal bearing load for open propeller
- block size may have an important effect on horizontal bearing load maximum on nozzle propeller
- generally the magnitude of the maximum and minimum horizontal bearing load increase moderately with RPS
- there is little difference in response between the nozzled and open propellers
- one exception is with the nozzled propeller and 400 mm blocks where the maximum bearing load is comparably higher than the other test results
- the average of the bearing load stays very close to the hydrodynamic value.
- vertical bearing load amplitude appears to be higher in nozzle, in comparison with the open propeller especially in small ice blocks.
- block size does not influence vertical bearing load in nozzle.
- for the open propeller minimum vertical bearing load increases dramatically with block size

Low Pitch:

The effect of RPS for low pitch is shown in Fig. 4.4.7 for both horizontal and vertical bearing load. The loads are systematically lower than for higher pitch. Otherwise the results are similar to higher pitch results.

4.4.3 Horizontal Bearing Load vs. Velocity

Hydrodynamic Loads:

The hydrodynamic horizontal bearing load vs. velocity for 7.5 RPS, high pitch, ducted and open propellers is shown in Fig. 4.4.8. The effect of velocity on the hydrodynamic horizontal bearing load appears to be negligible. The horizontal bearing load is greater in magnitude for the ducted screw than for the open screw.

Also velocity has little effect on the vertical bearing load. The load in the ducted screw case is higher than that in the open screw case.

Block Loads:

Figure 4.4.9 shows the effects of velocity on horizontal bearing load for 7.5 RPS, high pitch, nozzled and open propellers, 100 mm thick ice, and all block sizes. The observed trends are:

- velocity appears to have no effect on horizontal bearing load for all maximum, minimum, and average responses
- block sizes has no effect on the horizontal bearing load
- no difference exists between nozzled and open propellers
- the minimum vertical bearing load is unaffected by velocity
- the maximum vertical bearing load is unaffected by velocity for the nozzled propeller
- the maximum vertical bearing load slightly increases with velocity for the open propeller
- influence of velocity on vertical bearing load is similar for all block sizes.
- the nozzled propeller vertical bearing load response tends to be slightly larger than the open propeller response

Low Pitch:

Fig. 4.4.11 shows the effect of velocity on bearing loads for low pitch, 100 mm thick, 400 mm blocks. Observations:

- the influence of velocity is negligible or negative for nozzle propeller.
- the minimum bearing load increases with speed for open propeller.

5. SHAFT THRUST AND TORQUE DATA ANALYSIS

5.1 General

Shaft thrust and torque propeller/ice interaction data are composed of three main components.

Shaft thrust and torque propeller/ice interaction load = Open water hydrodynamic load

+ Indirect ice load due to the propeller working in the hydrodynamic disturbance caused by the presence of ice

+ Direct ice load due to contact of propeller with ice.

Each of these components is in general affected in different ways and to different extents by propeller design, environmental and operational parameters. It is therefore necessary to separate these components and determine their separate parametric dependencies in order for the model test data to be applied to any given propeller design, environmental and operational scenario.

An analysis of this kind has not previously been attempted. It was therefore necessary to develop a procedure based on an understanding of the components and on the nature and evidence observed from the model test data.

5.1.1 Global Analysis Procedure

The key element in the analysis procedure is the parametric dependency of the direct ice load on the ice flexural strength. This is because:-

- In establishing this relationship, the validity of the physical models for determining the indirect ice loads can be confirmed.
- By the nature of ice model testing, ice strength varied continuously throughout the tests. Understanding and correction for ice strength effects is subsequently necessary before the dependency of the other test parameters, which were controlled in a systematic fashion, can be determined accurately.

Influence of Ice Strength

In Chapter 3 it is described how the test parameters were varied in order that the influence of any single parameter upon propeller loading could be determined for many combinations of the remaining parameters. Ice strength is the one parameter which could not be controlled accurately in a predetermined manner. Its variation within the test program was therefore not as systematic as for the remaining parameters. Nonetheless, the test programme yielded sufficient data, for cases where specific combinations of remaining parameters were tested in a good range of ice strengths, for the influence of ice strength to be determined.

In the test programme, the following list of experiments were carried out in order to determine the influence of ice strength. In each case, specific combinations of parameters were tested at two ice strengths.

TABLE 5.1.1.1

Day	Run Nr.	Ice Th.	RPS	V m/s	Pitch	Nozzle	Blocks	Strength
2	11	100	3.7	0	H	Y	100 200	29
2	12	100	3.7	0	H	Y	400	29
2	29	100	3.7	0	H	Y	ALL	19.1
2	30	100	3.7	0	H	Y	400	18.9
2	14	100	7.5	0	H	Y	ALL	28.1
2	28	100	7.5	0	H	Y	ALL	19.3
3	4	100	7.5	0	H	N	200 400	17.9
3	17	100	7.5	0	H	N	ALL	17.0
3	6	100	3.7	0	H	N	ALL	17.8
3	16	100	3.7	0	H	N	ALL	17.0
4	4	50	7.5	0	H	Y	ALL	59.5
4	20	50	7.5	0	H	Y	ALL	28.3

It is seen that the most suitable data sets for investigating the effect of ice strength on propeller loading are :-

Runs 14 and 28 }
} in the thicker, weaker ice
Runs 11,12 and 29,30 }

Runs 4 and 20 in the thinner, stronger ice,

since these combinations offer the largest variations in the ice strength parameter. It will be noted that these data sets are for the ducted propeller case.

Ducted Propeller - Shaft Torque

Figure No. 5.1.1.1 is presented as an example of the manner in which shaft loading was found to be affected by ice flexural strength. This figure presents model scale shaft torque in Newton-metres (Nm) as the ordinate versus ice flexural strength in kiloPascals (kPa) as the abscissa. The data are for 200 mm square, 100 mm thick blocks from run numbers 14 and 28. Ice strengths were respectively 28.1 and 19.3 kPa.

Figure No 5.1.1.1 shows the following model data points:

- The mean open water hydrodynamic torque, Q(o,mean) for the ducted propeller at high pitch, 7.5 RPS shaft speed in bollard condition.
- The mean torques during ice milling (Q(m,mean) diamond points) for each of three blocks at each of the two ice strengths.
- The maximum torques during ice milling (Q(m,max) crosses) for each of three blocks at each of the two ice strengths. In addition, two other points are shown in Figure No 5.1.1.1 at zero ice strength.

- The mean and maximum hydrodynamic torques during ice blockage (Q(b,mean) and Q(b,max)) as determined from the indirect ice load analysis given below in Section 5.2.2. These loads can be visualized as those resulting from the propeller working in the disturbed flow immediately behind a 200mm square, 100mm thick ice block of zero strength during the milling process.

In Figure No 5.1.1.1, the mean and maximum torques during the milling process are now described at three ice strengths, 0, 19.3 and 28.1 kPa. It will be noted that there is some degree of variability in the positive ice strength data, particularly the maxima. This is due to the natural random element, or degree of variability in the experiments themselves, whereby the blocks could contact the propeller blades at somewhat different attitudes to and locations within the propeller disc. Three blocks were tested at each combination of parametric variables in order that the probable maximum values, and therefore correct figures for these purposes of Q(m,mean) as well as Q(m,max) should be obtained. In the majority of cases the nature of the spread of data values supports this approach. The maximum value of the three loadings at each ice strength is therefore taken as the maximum loading likely to occur for that combination of test parameters.

The required mean and maximum milling torques are therefore now defined at three ice strengths and the nature of the direct ice loading on the shaft relative to ice strength is clearly best defined as linear. The manner in which both the mean and maximum torques follow the same trend with ice strength also supports the indirect ice load model established from the analysis in Section 5.2.2 below.

The composition of the shaft torque propeller/ice interaction load for the ducted propeller at any given ice strength can now be described as follows with reference to Figure No. 5.1.1.1.

- Maximum shaft torque during milling Q(m,max) = Open water hydrodynamic load Q(o,mean)

  + Indirect ice load due to blockage occurring during milling Q(b,max)-Q(o,mean)

  + Direct ice load due to milling which is linearly dependent upon ice strength sigma (Q(m,max)-Q(b,max))/sigma)

- Mean shaft torque during milling Q(m,mean) = Open water hydrodynamic load Q(o,mean)

  + Indirect ice load due to blockage occurring during milling Q(b,mean)-Q(o,mean)

  + Direct ice load due to milling which is linearly dependent upon ice strength sigma (Q(m,mean)-Q(b,mean))/sigma)

Ducted Propeller - Shaft Thrust

An exactly similar analysis cannot be carried out for shaft thrust since, in a high percentage of cases, ice blocks bore on the propeller hub, which was not isolated from the propeller shaft dynamometer, and thereby provided an unwanted and unknown negative thrust component to the propeller milling thrust. This effect is demonstrated in Figure No. 5.1.1.2, the companion figure in thrust to Figure No. 5.1.1.1. However, although mean milling thrust is not reliably defined, the difference between maximum and mean will be unaffected. Figure No. 5.1.1.3 is therefore derived in order to demonstrate the influence of the ice strength parameter on shaft thrust.

In Figure No. 5.1.1.3 , the difference between maximum and mean thrust for each block is constructed above the appropriate mean blockage thrust. The missing element, therefore, relative to Figure No. 5.1.1.1 , is the change in mean thrust with increase in ice strength. The construction is, however, valid for the relationship between maximum minus mean thrust and ice strength. As shown previously in the case of torque, the maximum minus mean component of the direct ice load is again linear with respect to ice strength. The composition of the shaft thrust propeller/ice interaction load for the ducted propeller at any given ice strength can now be given as:=

- Maximum shaft thrust during milling T(m,max) = Open water hydrodynamic load T(o,mean)
  - + Indirect ice load due to blockage occurring during milling T(b,max)-T(o,mean)
  - + Direct maximum minus mean ice load component due to milling which is linearly dependent on ice strength sigma (T(m,max)-T(m,mean))/sigma)
  - + Direct mean ice load component due to milling of as yet unknown magnitude, although suspected to be relatively small and linearly dependent upon ice strength T(m,mean)-T(b,mean)

Open propeller Loads

The analysis procedure to separate direct and indirect ice loads for the open propeller is similar to that described above for the ducted propeller, except that the indirect ice load due to nozzle blockage is replaced by the pre-milled load. This is the hydrodynamic load resulting from the propeller blades operating within the milled portion of an ice block during the milling process. Demonstration of the applicability of the linear dependency of direct ice load on ice strength is, however, not directly possible in this case, since , as seen in Table No. 5.1.1.1 , the range of ice strength is very small. However, having demonstrated a linear dependency for the propeller milling ice within the nozzle, it is considered entirely reasonable to adopt the same dependency for the open propeller. Furthermore, the logical , ordered nature of the subsequent results of the analysis support this approach.

An illustration of the effect of ice strength on milling load for the open propeller is given in Figure No. 5.1.1.4 , which shows shaft thrust for 200mm blocks, 100mm ice thickness in the high pitch, high RPS , bollard condition.

The composition of the shaft loads during propeller/ice interaction for the open propeller can now be described as follows:=

- Maximum shaft torque during milling Q(m,max) = Open water hydrodynamic load Q(o,mean)
  + Indirect pre-milled ice load Q(p,max)-Q(o,mean)
  + Direct ice load due to milling sigma((Q(m,max)-Q(p,max))/sigma

- Mean shaft torque during milling Q(m,mean) = Open water hydrodynamic load Q(o,mean)
  + Indirect pre-milled ice load Q(p,mean)-Q(o,mean)
  + Direct ice load due to milling sigma((Q(m,mean)-Q(p,mean))/sigma)

- Maximum shaft thrust during milling T(m,max) = Open water hydrodynamic load T(o,mean)
  + Indirect pre-milled ice load T(p,max)-T(o,mean)
  + Direct maximum minus mean ice load component due to milling sigma((T(m,max)-T(m,mean))/sigma)
  + Direct mean ice load component due to milling of as yet unknown magnitude T(m,mean)-T(p,mean)

Summary

The above analysis has shown, by using data at three ice strengths (zero or hydrodynamic plus two positive ice strengths), that the direct ice loads during milling are linear with respect to ice strength. This knowledge allows the direct ice loads to be expressed in terms of thrust or torque loading per unit ice strength , whereby parametric dependencies other than that of ice strength might be determined. Furthermore, this index of ice load may be determined with the knowledge of ice loading at only one positive ice strength value, as is the situation in the majority of cases.

In addition the analysis has also confirmed the correct interpretation and selection of the indirect ice load models.

5.2 Individual Tests Data Analysis

In the following Sections, the data analysis of the individual type tests, contributing specific components in the thrust and torque identities given above, are described.

5.2.1 Hydrodynamic Tests

Open water shaft thrust and torque hydrodynamic data are required within the project in order to provide basic reference values. These are used in the following manner.

- To subtract from propeller total milling loads in order to isolate the direct and indirect ice loads for subsequent analysis.
- To provide open water reference values of thrust, torque or power with which to compare the magnitude of ice interaction loads.

During the model test programme, these open water hydrodynamic data were subject to some small variations. This was due to the fact that, by design, basic model physical parameters were continually changed and it was not possible in every instance to reproduce precisely a required group of parametric settings. Propeller blade pitch presented the largest problem, it being found extremely difficult to set the pitch angle on any blade accurately.

The problem of data variation was treated in the following manner.

- For each individual model test group - that is, each combination of open or ducted propeller, pitch setting, shaft speed, advance speed and test type - including repeat tests, a separate hydrodynamic reference test was run. Subsequently, in the analysis of each model test, its own hydrodynamic reference data were used exclusively.
- Where the hydrodynamic data were required as a reference level for the results of a global test analysis, the mean of all data were used. These mean open water hydrodynamic data are given in Table No 5.2.1.1.

5.2.2 Blockage Tests

Two separate analyses for blockage of the ducted propeller were carried out.

- The flat plate blockage tests carried out for comparison with previous similar tests carried out by Wartsila in a cavitation tunnel.
- Ice block blockage events which occurred naturally during the test programme.

Flat Plate Blockage

These tests were carried out in the bollard condition, at both high and low pitch, three shaft speeds of 3.7, 5.6 and 7.5 RPS and at blockages of 0, 10, 20, and 30 % of the propeller disc area excluding hub area. As in all of the model tests, the shaft thrust and torque signals were recorded in analogue form and later digitized at a sampling rate of 50 Hz. Mean and maximum thrust and torque values were then determined from the digitized data.

The results of the experiments are given in graphical form in the following figures.

Figures 5.2.2.1-3.Torque v Blockage for high pitch, all RPS.
Figures 5.2.2.4-6.Torque v Blockage for low pitch, all RPS.
Figures 5.2.2.7-9.Thrust v Blockage for high pitch, all RPS.
Figures 5.2.2.10-12.Thrust v Blockage for low pitch, all RPS.

In each figure, the shaft loading in thrust or torque is composed of the elements :

- Open water hydrodynamic maximum and mean values at zero blockage, T(o,max), T(o,mean), Q(o,max)and Q(o,mean).
- Hydrodynamic blockage maximum and mean values. T(b,max), T(b,mean), Q(b,max), Q(b,mean).

The data are additionally presented in the form showing the change in shaft loading with RPS for different values of blockage. In this case, only the indirect load components are included.

Figure 5.2.2.13. T(b,max)-T(b,mean) v RPS for high pitch.
Figure 5.2.2.14. T(b,max)-T(b,mean) v RPS for low pitch.
Figure 5.2.2.15. T(b,mean)-T(o,mean) v RPS for high pitch.
Figure 5.2.2.16. T(b,mean)-T(o,mean) v RPS for low pitch.
Figure 5.2.2.17. Q(b,max)-Q(b,mean) v RPS for high pitch.
Figure 5.2.2.18. Q(b,max)-Q(b,mean) v RPS for low pitch.
Figure 5.2.2.19. Q(b,mean)-Q(o,mean) v RPS for high pitch.
Figure 5.2.2.20. Q(b,mean)-Q(o,mean) v RPS for low pitch.

Ice Block Blockage

During the course of the ice block tests, thirteen cases of blockage occurred naturally with 400mm and 200mm square blocks. These blockage events are listed in Table 5.2.2.1. It will be noted that the events include 50mm and 100mm thick ice, high and low pitch, zero and 1.0 m/s forward speed and all RPS. Six types of blockage were analyzed from the video records. These are shown diagrammatically in Figure 5.2.2.21 and noted in Table 5.2.2.1.

Analysis of the video record demonstrated very clearly that the blockage type which most closely represents the position and attitude of blocks during the milling process is blockage Type 4, which occured in 5 cases of 400mm square blocks of thickness 100mm and 50mm and at shaft speeds of 5.6 and 7.5 RPS. During both the ice block and level ice tests, individual blocks of ice were drawn towards the propeller disc with a face of least thickness(the ice thickness) leading and very close to parallel with the propeller disc, the larger faces of the blocks being virtually perpendicular to the propeller disc. This is the attitude shown by blockage Type 4. It was therefore clear that, if found necessary in the analysis, the data from the Type 4 blockages should be given precedence. Furthermore, it was determined from analysis of the time traces of thrust and torque, that the blockage events were preceded by short duration milling. This indicates that the ice block blockages correctly simulate the situation required for the direct determination of the indirect ice loads during milling. That is, the ice block should provide very close blockage of the propeller without having contact. In this situation, the shaft thrust and torque measurements yield the required indirect blockage ice loads. These are:-

Q(b,max)-Q(o,mean)
Q(b,mean)-Q(o,mean)
T(b,max)-T(o,mean)
T(b,mean)-T(o,mean)

The numerical value of these blockage loads were determined from the 50Hz digitized data and are tabulated in Table 5.2.2.1.

It was now necessary to establish the indirect loads for all combinations of test parameters from the results of the thirteen blockage cases. This was clearly not possible without judicious use of other test data, as described in the steps below.

- The variation of ice block blockage loads with shaft speed should follow the same qualitative trends as those for flat plate blockage. The ice block blockage data were therefore plotted on the flat plate blockage curves in Figures 5.2.2.13 to 5.2.2.20, as shown in Figures 5.2.2.22 to 5.2.2.29.

- For the term T(b,max) - T(b,mean) , Figures 5.2.2.22 and 5.2.2.23.
  Draw curves through data points at 5.6 and 7.5 RPS with similar shape as flat plate curves. These data are predominantly for Type 4 blockage and therefore more representative than the proportionately higher points at 3.7 RPS. On consideration of the blockage types other than Type 4 in Figures 5.2.2.22 and 5.2.2.23, it appears consistent that blockages where the blocks are angled across the nozzle should result in higher loads as shown at 3.7 RPS. Curves are now determined for the following bollard cases:-

  High pitch, 400mm blocks, 100mm thick.
  High pitch, 400mm blocks, 50mm thick.
  Low pitch, 400mm blocks, 100mm thick.
  Low pitch, 200mm blocks, 100mm thick.

These curves show:-

- 200mm block data are 82% of 400mm block data (also shown by similar ratio at 3.7 RPS)
- Low pitch data are 62% of high pitch data.
- 50mm ice thickness data are 46% of 100mm data.

This analysis establishes the data shown in Table 5.2.2.2.

- For the term T(b,mean) - T(o,mean), Figures 5.2.2.24 and 5.2.2.25.

Only five data points are available since ice was clearly bearing on the propeller hub in the remaining tests. These data provide curves for:

High pitch, 400mm blocks, 100mm thick.
High pitch, 400mm blocks, 50mm thick.

They show that 50mm ice thickness data are again 46% of 100mm data. In addition the following relationships are used. For flat plate blockage, pitch has negligible effect upon this mean thrust term. Assume the same for block blockage. Assume, as with the data maximums, that 200mm block data are 82% of the 400mmblock data.

This analysis establishes the appropriate data in Table 5.2.2.2.

- For the term Q(b,max) - Q(b,mean) , Figures 5.2.2.26 and 5.2.2.27.

The analysis is carried out in the same manner as for thrust. The same relationships are noted for Type 4 blockages relative to other types of blockage and the same ratios are established as follows:

- 200mm block data are 82& of 400mm block data.
- Low pitch data are 62% of high pitch data.
- 50mm ice thickness data are 46% of 100mm data.

This analysis establishes the data shown in Table 5.2.2.2.

- For the term Q(b,mean) - Q(o,mean) , Figures 5.2.2.28 and 5.2.2.29.

The analysis is carried out in the same manner as for thrust and similar relationships are noted. The data show the following ratios:

- Low pitch data are 40% of high pitch data.
- 50mm ice thickness data are 46% of 100mm data.

The 200mm block data are slightly higher than 400mm block data (for low pitch, high RPS). This is clearly erroneous and the previously established ratio of 82% is used.

This analysis establishes the last data in Table 5.2.2.2.

- The data for forward speed of 1 m/s are very few but generally show a very small reduction relative to bollard. It was concluded, that without further information, the only reasonable course of action was to adjust all data for forward speed in the same manner as open water data. Tables 5.2.2.3 and 5.2.2.4 give these corrected data for forward speeds of 0.2 and 1.0 m/s .

5.2.3 Pre-Milled Tests

These tests were carried out in the bollard condition, at only low pitch and 7.5 RPS. Three levels of pre-milled indirect loading were investigated, 10%, 20% and 30%. This percentage refers to the ratio of the milled area of a block to the propeller disc area. The results of the experiments are given in graphical form in the following figures.

Figure 5.2.3.1.Torque v Pre-milled % for low pitch, 7.5 RPS.
Figure 5.2.3.2.Thrust v Pre-milled % for low pitch, 7.5 RPS.

In each figure, the shaft loading in thrust and torque is composed of the elements :-

- Open water hydrodynamic maximum and mean values at zero pre-milled condition, T(o,max), T(o,mean), Q(o,max), Q(o,mean).

- Hydrodynamic pre-milled maximum and mean values, T(p,max), T(p,mean), Q(p,max), Q(p,mean).

It was now necessary to establish the pre- milled indirect loads for the open propeller for all combinations of test parameters from these limited results. The terms required were:-

Q(p,max)- Q(o,mean)
Q(p,mean) - Q(o,mean)
T(p,max) - T(o,mean)
T(p,mean) - T(o,mean)

The variables which define these indirect loads are the pre-milled percentage, which is a function of the depth of cut of the propeller blades into an ice block, RPS, pitch and forward speed. In these experiments, block size and thickness were not significant parameters since they did not affect the area of ice which was milled.

Careful examination of the test video records showed that the maximum depth of cut in any group of ice block tests was as close to 50mm as could be reasonably measured. 50mm thick blocks were cut through at maximum penetration and 100mm blocks were cut to half depth of the block and individual blades. This cut depth of 50mm for both 200mm and 400mm square blocks is equivalent to a pre-milled percentage of 12%.

The indirect, pre-milled loads for 7.5 RPS, low pitch, bollard condition, from Figures 5.2.3.1 and 5.2.3.2 are therefore:-

Q(p,max) - Q(o,mean) = 50 N
Q(p,mean) - Q(o,mean) =14 N
T(p,max) - T(o,mean) = 3.4 Nm
T(p,mean) -T(o,mean) =0.5 Nm

These data now require modification for the effect of RPS change from 7.5 to 5.6 and 3.7, change from low to high pitch and from bollard to 0.2 and 1.0 m/s. However, no information are available on such modification since this is the first application of the new pre-milled concept in the analysis of open screw ice loading. The only approach available to the project was to adopt the same quantitative trends as were measured and developed for the ice block blockage of the ducted propeller. From the physical standpoint, these trends would appear entirely reasonable, indirect loads increasing significantly with increase in pitch , decreasing significantly with decrease in RPS and decreasing moderately with increase in forward speed. It must however be borne in mind that the numerical value of the data modifications are not proven.

Applying these quantitative trends from Tables 5.2.2.2 to 5.2.2.4, to the data above for low pitch , bollard and 7.5 RPS , yields the pre-milled hydrodynamic loads in Table 5.2.3.1.

5.2.4 Individual Block Tests

The individual block tests were analyzed as described in Section 5.1.1, Global Analysis Procedure, above, using the Open Water and Indirect Ice loads as developed in Sections 5.2.1 , 5.2.2 and 5.2.3 . For each combination of test parameters, the maximum and mean values of shaft load during the ice block group tests were first determined. The appropriate open water and indirect ice loads were then subtracted, leaving the direct ice milling load. This was then divided by the ice flexural strength and the resulting direct ice load indices of thrust and torque loading per unit ice strength were then cross plotted in order to investigate the influence of individual parameters.

The analyzed data are given in the following Tables.

Table 5.2.4.1 . Ducted screw, high pitch, bollard.
Table 5.2.4.2 . Ducted screw, high pitch, 0.2 m/s.
Table 5.2.4.3 . Ducted screw, high pitch, 1.0 m/s.
Table 5.2.4.4 . Ducted screw, low pitch, bollard.
Table 5.2.4.5 . Ducted screw, low pitch, 1.0 m/s.
Table 5.2.4.6 . Open screw, high pitch, bollard.
Table 5.2.4.7 . Open screw, high pitch, 0.2 m/s.
Table 5.2.4.8 . Open screw, high pitch, 1.0 m/s.
Table 5.2.4.9 . Open screw, low pitch, bollard, including very thick blocks.
Table 5.2.4.10 . Open screw, low pitch, 1.0 m/s.

The results for Q max, Q mean and T max direct ice load indices are plotted in the following figures.

Figures 5.2.4.1-3. Ducted screw, high pitch,bollard.
Figures 5.2.4.4-6. Ducted screw, high pitch, 0.2 m/s.
Figures 5.2.4.7-9. Ducted screw, high pitch, 1.0 m/s.
Figures 5.2.4.10-12. Ducted screw,low pitch,bollard.
Figures 5.2.4.13-15. Ducted screw,low pitch, 1.0 m/s.
Figures 5.2.4.16-18. Open screw, high pitch,bollard.
Figures 5.2.4.19-21. Open screw, high pitch, 0.2 m/s.
Figures 5.2.4.22-24. Open screw, high pitch, 1.0 m/s.
Figures 5.2.4.25-27. Open screw, low pitch, bollard.
Figures 5.2.4.28-30. Open screw, low pitch, bollard, very thick blocks.
Figures 5.2.4.31-33. Open screw, low pitch, 1.0 m/s.

5.2.5 Level Ice Tests

The level ice tests were analyzed in the same manner and using the same indirect ice load data as the individual block tests. This approach is not strictly correct since it involves the following approximations and assumptions.

- Indirect ice loads for the 200mm and 400mm cut width ice blocks are taken the same as for the individual blocks of 200mm and 400mm square. This is considered a reasonable choice, since the largest ice blocks generated in the level ice tests had dimensions very similar to the cut width.

- The approach assumes that the continuous stream of blocks generated in the level ice tests is dealt with separately and uniquely by the propeller. This may be reasonable for slow speed level ice tests at 0.2 m/s, where the video record showed very little indication of multiple block propeller/ice interaction, particularly for the open screw. However, with the much higher rate of ice block generation at 1m/s, multiple interactions clearly occured, almost continually. With the open propeller, ice blocks were barely slowed down at the propeller disc and the propeller simply ingested ice as it arrived. With the ducted propeller, however, ice was slowed down at the propeller disc such that a build-up of ice blocks occured. Multiple milling clearly took place, although not all the ice arriving at the propeller disc was subsequently milled, since the ice build-up in front of the propeller acted in part as a deflector. In the physical scenario described above, the indirect ice load will clearly be greater than for an individual block. However, just how much or how many times larger is not known . Nor whether the maximum and minimum components will be in the same ratio. It was subsequently decided to use the individual block data in the analysis and to bear the implications in mind in the interpretation of the results.

- The mean values of shaft loading in the level ice tests are averages of numerous consecutive events including loading gaps where they might occur. This would probably be only at slow speed. The mean values in the block tests, however, were for single interactions. This is probably a subtle difference relative to the effect above of multiple interactions.

The analyzed data are given in the following tables and figures:-

Table	Figures	
5.2.5.1	5.2.5.1-3	Ducted screw, high pitch, 0.2 m/s.
5.2.5.2	5.2.5.4-6	Ducted screw, high pitch, 1.0 m/s.
5.2.5.3	5.2.5.7-9	Ducted screw, low pitch, 0.2 m/s.
5.2.5.4	5.2.5.10-12	Ducted screw, low pitch, 1.0 m/s.
5.2.5.5	5.2.5.13-15	Open screw, high pitch, 0.2 m/s.
5.2.5.6	5.2.5.16-18	Open screw, high pitch, 1.0 m/s.
5.2.5.7	5.2.5.19-21	Open screw, low pitch, 0.2 m/s.
5.2.5.8	5.2.5.22-24	Open screw, low pitch, 1.0 m/s.

6.0 DISCUSSION OF TEST RESULTS

6.1 Hydrodynamic Tests

The open water hydrodynamic data for each individual block model test are given in the analysis sheets for individual block tests, Tables 5.2.4.1-10. It is noted that differences of a few per cent occur in the mean thrust and torque data for any specific parameter group of pitch, RPS and forward speed.
In the analysis for individual block model test groups, this difficulty was avoided by using exclusively the local hydrodynamic reference data. However, where the hydrodynamic data are required as a reference level for the results of a global test analysis, mean data, as given in Table 5.2.1.1, should be used. In viewing these data, it is observed that the process of taking the means of data for all similar parameter groups has not balanced out entirely the variability in the data. This is shown by the data at 0.2 m/s relative to those at 0 and 1.0 m/s. For both the ducted and open propeller, shaft thrust and torque should decrease progressively as forward speed increases. However, in Table 5.2.1.1 , the data for 0.2 m/s are marginally higher than for bollard condition instead of being 2 to 3 per cent less.

For this current project, the knowledge that the reference open water hydrodynamic means could be in error by 2 to 3 per cent is not a serious issue, since the realistic objectives of any global analyses in this new subject area, do not require this level of precision. The inaccuracy is believed to be due to the manual mechanism to set the pitch on each propeller blade individually, combined with the non lockable pitch mechanism which had a tendency to creep.

6.2 Blockage Tests

6.2.1 Flat Plate Blockage

The results for flat plate blockage in Figures 5.2.2.1-12, show that both maximum and mean values of blockage torque and thrust are well described as increasing from zero blockage linearly with respect to the degree of blockage. Additionally, from Figures 5.2.2.13-20, the following relationships are noted.

- Maximum and mean thrust and torque increase with increase in RPS in a greater than linear fashion.

- T(b,max)-T(b,mean) increases in going from low pitch (19 degrees) to high pitch (31 degrees). The percentage increase increases with the degree of blockage, reaching 30% at 30% blockage.

- T(b,mean)-T(o,mean) is virtually the same for both high and low pitch at all degrees of blockage.

- Q(b,max)-Q(b,mean) increases in going from low to high pitch. The percentage increase increases with the degree of blockage, exceeding 30% at 30% blockage.

- Q(b,mean)-Q(o,mean) increases markedly in going from low to high pitch. The increase of 154% is independent of the degree of blockage.

- In the area of moderate blockage, 15-20%, the magnitudes of :-
  T(b,max)-T(b,mean) and T(b,mean)-T(o,mean) and Q(b,max)-Q(b,mean) and Q(b,mean)-Q(o,mean) are reasonably similar, such that, as pitch decreases, maximum thrust decreases only slightly whilst maximum torque decreases significantly.

As stated in Section 5.2.2, the flat plate blockage tests were carried out for comparison with similar tests conducted by Wartsila in a cavitation tunnel. This comparison and the resulting analysis of whether these current tests might in any way be affected by a lack of correct scaling of the cavitation number is discussed in the main report . Visual observations at the time of the tests and of the video record gave no indication of cavitation phenomena in these atmospheric tank tests. There was no sign of cavitation on the propeller blades nor of cavitation bubbles in the wake.

6.2.2 Ice Block Blockage

It has been made clear in Section 5.2.2 that the derivation of the ice block blockage data in Table 5.2.2.1 is based on a limited number of blockage events, the data from which have been interpreted, modified and applied to the full range of test parameters according to the best available information and understanding of the phenomena. Clearly, therefore, the data cannot be claimed to be definitive, particularly with respect to those data for test parameters not included in the ice block blockage events. However, there can be no doubt that these unique data, which have not previously been isolated in any investigation, are a true reflection of the physical phenomenon of blockage occurring during the ice milling process.

The data are derived from situations where ice blocks were in the same attitude and position as if they were being milled, yet there was no propeller contact with the ice. The data therefore reflect the physical situation where the propeller blades pass the blocking ice blocks with virtually zero clearance. In this situation, high blade load impulses, and subsequently high peak loads, will occur. Mean loads, on the other hand, are the result of an overall reduction in flow caused by the blocking ice. Since the ice is edge-on to the propeller disc and allows flow to enter the propeller on both sides, (Figure 5.2.2.21, type 4 blockage) this means that mean blockage is unlikely to be severe.

This is certainly the situation reflected in the data in Table 5.2.2.2 , where the dynamic component of blocking load is always very much larger than the mean. The most dramatic examples are for the case of 400mm square, 100mm thick blocks at 7.5 RPS. At high pitch , T(b,max)-T(b,mean) is 4.1 times T(b,mean)-T(o,mean) and Q(b,max)-Q(b,mean) is 2.2 times Q(b,mean)-Q(o,mean), while at low pitch, T(b,max)-T(b,mean) is 2.5 times T(b,mean)-T(o,mean) and Q(b,max)-Q(b,mean) is 3.3 times Q(b,mean)-Q(o,mean).

The influence of shaft RPS on ice block blockage loads is taken as similar, in qualitative terms, to the influence measured in the flat plate blockage tests. This is supported by the ice block blockage data in six cases in Figures 5.2..2.22-29. Although the blockage loads in Table 5.2.2.2 reduce significantly with decrease in RPS, this reduction is by no means as rapid as that of open water hydrodynamic loads in Table 5.2.1.1. Therefore, relative to open water hydrodynamic loads (shaft thrust and torque), blockage loads increase with decreasing RPS.

The influence of block size from 400mm to 200mm square is determined to give a reduction to 82% of the loads. This is entirely realistic. Whereas only 250 mm side length of the 400mm square blocks can enter the nozzle, the full side length of the 200mm blocks, or 80% that for the larger blocks, can do so. Blockage thrust and torque loads are therefore approximately proportional to the side length of the blocks entering the nozzle.

The influence of ice thickness from 100mm to 50mm is determined to give a reduction to 46% of the loads. This is consistent with the above findings for block size and demonstrates, that for ice block blockage, the blockage loads are approximately proportional to blockage area.

Pitch reduction is determined to give a reduction to 62% of the loads. However, as with the effect of RPS above, the open water hydrodynamic loads reduce at a higher rate, such that, relative to these loads, blockage loads increase with reduction in pitch.

As a result of the above arguments and comparisons, there is a considerable degree of confidence in the data developed in Table 5.2.2.2. Additional confidence is also provided by the manner in which these data contribute to the overall analysis.

In Figure 5.1.1.1 , which demonstrates the linearity of the direct milling torque with ice strength, the ice block blockage torques from Table 5.2.2.2 are given at zero ice strength. It is noted that both the maximum and mean points are consistent with their respective positive ice strength counterparts. This supports the finding that the maximum loads are very much larger than the mean. This fact has not previously been demonstrated, model blockage measurements having been confined to the flat plate blockage case, where as shown in Section 6.2.1 , the maximum minus mean component of blockage torque is of similar size to the mean.

The investigation has shown that ice block blockage is significantly different to flat plate blockage. Ice block blockage is characterized by the blocking ice being in close proximity to the propeller blades, when the oscillatory hydrodynamic component of shaft thrust and torque is large in comparison with the mean values. With flat plate blockage, the oscillatory and mean values are of similar magnitude. Ice block blockage is clearly the correct form of blockage to employ in the analysis of propeller/ice milling events. It is also clear, that in any subsequent work of this nature, it would be advantageous to measure the blocking loads from correctly simulated blockage in a systematic, planned fashion , rather than accepting blockage events as they occur. This would entail measurement of loads while blocks of different sizes and thicknesses are held in the milling position within the nozzle.

6.3 Pre-Milled Tests

As described in Section 5.2.3, the pre-milled indirect ice loads in Table 5.2.3.1 are derived from a limited amount of direct test data which has been modified using the quantitative trends obtained for ice block blockage. Whereas this approach appears entirely reasonable, the numerical values cannot be claimed to be exact in every case. A fortunate element in the derivation of the data in Table 5.2.3.1 is that the range of parameters, and therefore scope for error, is reduced. This is because block size and ice thickness are replaced by the single parameter of blade cut depth which was sensibly constant in the tests.

The indirect pre-milled loads may be compared with the blockage loads reported above. The pre-milled, or open propeller indirect ice loads, are consistently lower than the ice block blockage, or ducted propeller indirect ice loads in conditions of high pitch, large blocks and thick ice. For low pitch, smaller blocks and thinner ice, however, the open propeller pre-milled loads are higher.

6.4 Individual Block Tests

As stated above in Sections 5.1.1 and 5.2.4, the Direct ice loads are expressed in the form of maximum and mean ice milling loads per unit ice flexural strength. The dependencies of these direct ice load indices upon test parameters - pitch, revs forward speed, block size and ice thickness - are discussed below. Direct ice load indices are given on model scale in the units Newtons and Newton-metres per kiloPascal, N/kPa and Nm/kPa.

6.4.1 Ducted Propeller

High Pitch, bollard. Table 5.2.4.1 , Figures 5.2.4.1-3.

The complete range of propeller revolutions and block sizes was tested in the high pitch, bollard condition.

- For each block size and ice thickness, maximum torque shows some small variations with RPS. However, these variations show no overall trends and the best description is that maximum torque is sensibly constant with respect to shaft revolutions.

- The maximum torque index increases with both block size and ice thickness. Both parameters are important, ice thickness being the more important. Doubling ice block size from 200mm square to 400mm square increases the torque index by approximately 50%, whereas doubling ice thickness from 50mm to 100mm increases the torque index by over 100%.

- The mean torque index again more than doubles with doubling ice thickness, but there is little noticeable effect in doubling of block size. Increase in shaft revolutions causes an increase in mean torque for thin ice but this effect is considerably reduced at 100mm ice thickness.

- The maximum thrust results show identical trends as maximum torque. Maximum thrust index is sensibly constant with respect to shaft revolutions, increases approximately 50% with block size from 200mm to 400mm square and more than doubles with a doubling of ice thickness.

High Pitch 0.2 m/s. Table 5.2.4.2, Figures 5.2.4.4-6.

Available data are for different blocks at 7.5 RPS.

- Maximum torque indices are less systematic with respect to block size and ice thickness than for the bollard condition. Results for thin ice are similar to those at bollard while those for 100mm ice thickness are on average almost double those at bollard.

- The mean torque indices are again less systematic than those at bollard. Results for thin ice are similar and those for thick ice a little higher than in the bollard condition.

- The maximum thrust indices are again less systematic than those at bollard. In this case, however, the results are on average a little lower than in bollard condition for both ice thicknesses.

High Pitch 1.0 m/s. Table 5.2.4.3, Figures 5.2.4.7-9.

Data are available at 3.7 and 7.5 RPS for most blocks.

- The maximum torque indices for 50mm ice thickness are similar in magnitude to those at bollard and are again sensibly constant with respect to shaft revolutions. The indices for 100mm ice thickness and 7.5 RPS are, however, approximately double those at bollard.

- The mean torque data are by no means as consistent as at bollard condition. On average, however, they show a moderate increase in torque index with increase in forward speed.

- The maximum thrust index again indicates little dependency upon shaft speed. Thrust index levels for the smaller blocks are a little lower than at bollard, while those for larger blocks are nearly 100% greater than at bollard.

Low Pitch , Bollard. Table 5.2.4.4, Figures 5.2.4.10-12.

Data are available for all blocks at 7.5 RPS and for the thicker blocks at 5.6 RPS.

- The maximum torque indices show an average increase over those at high pitch of about 50%.

- The mean torque indices are not as consistent as at high pitch. On average, however, they show similar levels as at high pitch.

- The maximum thrust indices are not as consistent as at high pitch. In this regard they are similar in nature to the indices for mean torque. On average, mean levels are higher than at high pitch.

Low Pitch 1.0 m/s. Table 5.2.4.5, Figures 5.2.4.13-15.

Data are available for all blocks at 7.5 RPS.

- The maximum torque indices for thin ice show a generally moderate increase over those at high pitch. The indices for thick ice, however, are reversed in value from that expected, but both data are lower than the corresponding indices at high pitch and 1.0 m/s.

- The mean torque indices for thin ice are significantly higher than at high pitch, whereas the mean level for thicker ice is very similar to that for high pitch and 1.0 m/s.

- The maximum thrust indices for thin ice are similar to those at high pitch. With thicker ice, however, the indices are reversed in value from that expected. The average value, however, is lower than that for high pitch at 1.0 m/s.

Summary for Ducted Propeller

- The Direct Ice Loads, expressed in terms of shaft thrust and torque per unit ice strength, are sensibly constant with respect to shaft speed for any given size and thickness of ice block.

- Shaft thrust and torque indices increase significantly with increase in the thickness of ice blocks. Increasing ice thickness from 50mm to 100mm generally more than doubles the indices.

- Maximum shaft thrust and torque indices increase with the size of ice block. Increasing ice block size from 200mm to 400mm square, increases the indices by approximately 50%. Mean shaft torque is relatively insensitive to ice block size.

- At high pitch, maximum shaft thrust and torque indices for thin ice are relatively insensitive to forward speed. For thick ice blocks, however, the indices increase by 50% to 100% in going from 0 to 1 m/s. Mean shaft torque is again relatively insensitive to forward speed for thin ice blocks but increases by 30% to 50% for thick blocks in going from 0 to 1 m/s.

- With reduction in pitch, maximum shaft thrust and torque indices generally increase at bollard and decrease at forward speed.

6.4.2 Open Propeller

High Pitch, bollard. Table 5.2.4.6, Figures 5.2.4.16-18.

The complete range of propeller revolutions and block sizes was tested in the high pitch, bollard condition.

- The thrust and torque ice load indices show a considerable amount of variation with shaft speed, particularly for the thicker blocks. Maximum torque shows a modest decline with increasing RPS except for 200mm square, 100mm thick blocks, where the decline is large. Mean torque shows little overall variation with RPS except for 400mm square, 100mm thick blocks, where the torque index increases sharply with RPS. Maximum thrust decreases with increase in RPS, the decline being small for thin blocks but large for thick blocks.

- The thrust and torque indices increase greatly with both block size and thickness. Both parameters are very important, ice thickness being the more important. Increasing ice block size from 200mm square to 400mm square leads to an average increase in the thrust and torque indices of less than 50% at 50mm ice thickness and 100% at 100mm ice thickness. Increasing ice thickness from 50mm to 100mm increases the direct ice load indices by a factor of between 5 and 10 for 200mm square blocks and a factor of 10 for 400mm square blocks.

High Pitch 0.2 m/s. Table 5.2.4.7, Figures 5.2.4.19-21.

Data are available for large blocks at 3.7 RPS and all blocks at 7.5 RPS

- For 50mm thick blocks, increase in forward speed to 0.2 m/s results in little change in the maximum torque index and a small increase in the mean torque and maximum thrust indices. For 100mm thick blocks, the results are mixed. Maximum torque reduces for 400mm blocks but changes little for 200mm blocks. Mean torque changes little for 400mm blocks but doubles for 200mm blocks. Maximum thrust shows significant reductions of over 50% for both block sizes.

High Pitch 1.0 m/s. Table 5.2.4.8, Figures 5.2.4.22-24.

Data are available for thin blocks at 3.7 RPS and all blocks at 7.5 RPS.

- For 50mm thick blocks, increase in forward speed to 1.0 m/s results in moderate increases in maximum torque and thrust indices and a large increase of 100% to 200% in the mean torque index. Again, for 100mm thick blocks, the results are mixed. Maximum torque increases slightly for 400mm square blocks but more than doubles for 200mm blocks. Mean torque decreases significantly for both block sizes. Maximum thrust increases moderately for both block sizes.

Low Pitch , Bollard. Table 5.2.4.9, Figures 5.2.4.25-30.

Data are available for thick blocks at 3.7 RPS and all blocks at 7.5 RPS. Additionally, very thick blocks at 7.5 RPS.

- The data show overall far less variation with shaft speed than for the high pitch condition. Maximum torque decreases slightly with increase in RPS for 400mm square, 100mm thick blocks but increases slightly for 200mm square blocks. The maximum thrust index decreases slightly in both cases. Mean torque, however, increases significantly with RPS.

- The data show the similar large increases with increasing block size and thickness as in the high pitch case. For 50mm block thickness, the reduction in pitch results in a moderate increase in thrust and torque indices. In the case of 100mm thick blocks, the average values of the thrust and torque indices are slightly smaller than the corresponding high pitch results.

- The plots for very thick blocks, Figures 5.2.4.28-30, show that direct ice load indices for the open propeller continue to increase as ice thickness increases from 100mm to 200mm. The increase is proportionately greater than that which occurs below 100mm ice thickness. Increases in maximum torque, mean torque and maximum thrust indices as block thickness increases from 100mm to 200mm are approximately 200%, 150% and 275%.

Low Pitch 1.0 m/s. Table 5.2.4.10, Figures 5.2.4.31-33.

Data are available for all blocks at 7.5 RPS.

- Increase in forward speed at low pitch results in significant increases in thrust and torque indices for the 50mm thick blocks. This applies particularly to the 400mm square blocks. In the case of the 100mm thick blocks, moderate increases occur in maximum torque for both block sizes, very large increases occur in mean torque for both block sizes and the results for maximum thrust are mixed. A reduction occurs for 400mm square blocks, but a very large increase occurs for 200mm square blocks.

Discussion for Open Propeller

- The direct ice load data show far more variability than the corresponding data for the ducted propeller. This is particularly noticeable for the effect of the parameters of shaft speed, pitch and forward speed. In general, the effects of ice block size and thickness are almost as well defined as for the ducted propeller. It is concluded that this variability in results is inherent in individual block tests with an open propeller. Detailed examination of the video records shows that although the ice blocks approach the propeller disc in approximately the same manner, with one edge square-on to the plane of the propeller disc, small differences in attitude and linear and angular momentum occur. These differences are most clearly seen in the movement of the ice blocks during and after milling interaction. In the same nominal conditions, separate ice blocks may be milled as they proceed almost straight ahead, may rotate as they are milled, may be deflected radially, or any combination of these movements. Clearly, the open propeller interacts with ice blocks in a variety of ways, depending upon the particular initial conditions and this results in some variability in shaft loading for the same nominal conditions. Another aspect of this variability is the depth of cut. This was judged to be a maximum of 50mm for all block sizes and thickesses, but measurement of this dimension cannot be claimed to be precise, even from a high quality video. Propeller/ ice interaction is an extremely dynamic event and is always physically clouded to some extent by small ice particles. Inaccuracies in the depth of cut result in errors in the pre-milled forces and subsequently in the direct ice forces. Moreover, as has been discussed previously, derivation of the pre-milled forces is not claimed to be precise, especially for the high pitch condition which shows the greatest degree of variability. In view of the above, the degree of variability in the results is understandable. The reason for the relatively accurate definition of direct ice loads for the ducted propeller follows logically from the above. In the case of the ducted propeller, the manner in which ice blocks approach the propeller blades is more strictly controlled. First, the stronger upstream flow of the propeller will result in the ice blocks arriving in a more dynamically stable condition. Then, much of the linear and angular variation in momentum of approaching ice blocks, particularly the larger blocks, is destroyed by contact with the nozzle and the blocks subsequently feed into the propeller in a more controlled, uniform manner. In addition, the ice block blockage data are considered overall to be more accurate than the pre-milled data. As a result, the ducted propeller direct ice loads should show less variation than those for the open propeller, which they do. In view of the above, the summary of results must be somewhat more general than for the ducted propeller, using all available data and bearing in mind the relative degree of confidence in each case.

Summary for Open Propeller

- Taking into account both high and low pitch data, the general effect of shaft speed upon direct ice loads for the open propeller is :-
    - Maximum torque decreases slowly with increase in shaft speed.
    - Mean torque increases moderately with increase in shaft speed.
    - Maximum thrust decreases moderately with shaft speed.

- The thrust and torque indices increase greatly with both block size and thickness. Block size increase results in ice load increases of 50% to 100%. Ice thickness increase from 50mm to 100mm results in increases from 500% to 1000%. Moreover, as ice thickness continues to increase from 100mm to 200mm, the direct ice load indices increase relative to those at 100mm thickness by an additional 200% to 300%.

- Increase in forward speed generally increases the loads for the thinner ice blocks, especially the larger ice blocks. For the thicker ice blocks, the effect of forward speed is mixed. On average, the effect is neutral.

- Reduction in pitch causes a moderate increase in direct ice loads for thinner ice blocks and, on average, a small decrease for thicker ice blocks.

Ducted versus Open Propeller

Additional observations on the general level of thrust and torque direct ice loads on the two propulsion systems are as follows.

- There are both similarities and differences between the direct loads for the ducted and open propeller. The similarities are mainly in parametric dependencies and the differences are mainly in the magnitude of loads.

- Shaft loading indices for the ducted propeller are sensibly constant with respect to shaft speed. From the individual ice block tests alone, the indices for the open propeller show some moderate variation with shaft speed.

- Shaft loading indices for both the ducted and open propeller increase significantly with increase in block size and block thickness. Block thickness is the more important parameter.

- Increasing block size from 200mm square to 400mm square, increases load indices by 50% for the ducted propeller and 50-100% for the open propeller.

- Increasing block thickness from 50mm to 100mm, increases load indices by 100% at bollard and by up to 400% at 1 m/s for the ducted propeller and by 500-1000% at bollard for the open propeller.

- As a result of the above, the maximum direct load indices for the open propeller and the largest, thickest blocks, are some 3 to 4 times larger at bollard than the equivalent case for the ducted propeller. For thin blocks of both sizes, the load indices are very similar in magnitude.

- Increase in forward speed with thick blocks gives rise to a moderate increase in maximum load indices for the ducted propeller but has little effect on the open propeller.
- Reduction in pitch with thick blocks gives rise to a moderate increase in maximum load indices for the ducted propeller at bollard, but a small decrease for the open propeller.

6.5 Level Ice Tests

The direct ice loads are analyzed and expressed in the same manner as for the individual block tests. As explained above in Section 5.2.5, however, the correction made for the indirect loads assumes that the propeller mills one broken ice piece at a time. This will not be strictly correct, especially in conditions where the rate of arrival of ice blocks at the propeller is high and the propeller mills blocks slowly.

Individual ice block indirect loads are used in the analysis since the effect of multiple milling on indirect loads is not known.

6.5.1 Ducted Propeller

High Pitch, 0.2 m/s. Table 5.2.5.1, Figures 5.2.5.1-3.

- For 50mm ice thickness, thrust and torque load indices are independent of shaft speed.
- 100 mm ice thickness data at 0.2 m/s are not available at two shaft speeds for relationship to be determined.
- Load indices increase with ice thickness and width of cut. The increase with cut width is small in 50mm ice but large - 100% for torque, 300% for thrust - in 100mm ice. The increase with ice thickness is up to 400% for torque and 300% for thrust .

High Pitch, 1.0 m/s. Table 5.2.5.2, Figures 5.2.5.4-6.

- For 50mm ice thickness, thrust and torque load indices are independent of shaft speed. In 100mm ice, torque increases moderately and thrust increases rapidly with increases in shaft speed
- In 50mm ice, load indices increase with the width of cut by up to 100%.

- Increase in speed from 0.2 to 1.0 m/s, results in increases in load indices of 50% in thin ice, and of 80% and 400% for torque and thrust respectively in 100mm ice.

Low Pitch, 0.2 m/s. Table 5.2.5.3, Figures 5.2.5.7-9.

- Reducing pitch at 0.2 m/s causes significant increases in the load indices in both ice thicknesses.

Low Pitch, 1.0 m/s. Table 5.2.5.4, Figures 5.2.5.10-12.

- Thrust and torque indices for both ice thicknesses increase moderately with increase in shaft speed.
- At 1.0 m/s in thin ice, reduction in pitch approximately doubles the load indices. In thick ice, the effect of pitch is relatively smaller.

Summary for Ducted Propeller

- In 50mm ice, at high pitch, the load indices are independent of shaft speed. In 100mm ice at both pitches and 50mm ice at low pitch, the load indices increase moderately with increase in shaft speed.
- Load indices increase with ice thickness, the width of cut, and forward speed. All are important, but forward speed and ice thickness are more important than width of cut.
- Reduction in pitch increases the load indices in thin ice but has little effect in thick ice.

6.5.2 Open Propeller

High Pitch, 0.2 m/s . Table 5.2.5.5, Figures 5.2.5.13-15.

- In both ice thicknesses, thrust and torque load indices are independent of shaft speed.
- Load indices increase slightly with the width of cut.
- Load indices increase by approximately 400% as ice thickness increases from 50mm to 100mm.

High Pitch, 1.0 m/s . Table 5.2.5.6, Figures 5.2.5.16-18.

- Maximum thrust indices in 50mm ice and maximum torque indices in 100 mm ice are independent of shaft speed.
- Maximum torque indices in 50 mm ice and maximum thrust

indices in 100 mm ice increase by 100% as shaft speed increases from 3.7 to 7.5 RPS.

- Mean torque indices are independent of shaft speed in 50mm of ice and increase slowly with shaft speed in 100mm of ice.
- Increase in speed from 0.2 to 1.0 m/s in 50mm ice, increases all load indices by 100%.
- Increase in speed from 0.2 to 1.0 m/s in 100 mm ice, increases maximum torque by 60%, mean torque by 400%, but has no overall effect upon maximum thrust.
- No data are available for the determination of cut width effect.

Low Pitch, 0.2 m/s. Table 5.2.5.7, Figures 5.2.5.19-21.

- Reduction in pitch at 0.2 m/s results in increases in direct load indices of between 20% and 50%.

Low Pitch, 1.0 m/s. Table 5.2.5.8, Figures 5.2.5.22-24.

- In 100mm thick ice, the maximum thrust index increases by 50% as shaft speed increases from 3.7 to 7.5 RPS. Mean torque increases by 40%, but maximum torque is independent of shaft speed.
- Reduction in pitch at 1.0 m/s results in increases in maximum and mean torque indices of 60% to 80% in 50mm ice and 20% to 30% in 100mm ice. For maximum thrust the increases are 40% in 50mm ice and 150% in 100mm ice.
- Increase in forward speed at low pitch results in increases in maximum thrust and torque indices of between 70% and 200% in thin ice and 75% to 100% in thick ice.
- Increase in ice thickness at low pitch results in increases in maximum thrust and torque indices of 300% and 200% respectively. Mean torque increases by 300%.

Summary for Open Propeller

- At high pitch, for both ice thicknesses and speeds, the load indices are essentially independent of shaft speed, except for maximum thrust in 100mm ice at 1 m/s and maximum torque in 50 mm ice at 1 m/s which increase by 100% as shaft speed increases from 3.7 to 7.5 RPS.
- At low pitch in 50 mm ice, maximum thrust and torque increase moderately with increase in shaft speed.

- At low pitch in 100 mm ice, maximum torque is independent of shaft speed while mean torque and maximum thrust increase moderately with increase in shaft speed.

- Direct load indices increase slightly with increase in cut width.

- Direct load indices increase sharply with increase in ice thickness by 400% at high pitch and 300% at low pitch.

- Direct load indices increase with increase in speed from 0.2 to 1.0 m/s by 200% in thin ice and up to 100% in thick ice. The exceptions are mean torque, which increases by 400% and maximum thrust which is unaffected in thick ice.

- Reduction in pitch increases maximum thrust in thick ice at 1.0 m/s by 150% , but otherwise causes lower increases of 20% to 50 % in thick ice and 60% to 80% in thin ice.

Ducted versus Open Propeller

- Taken overall, the direct load indices for the ducted and open propellers display a significant level of similarity, both in terms of parametric trends and absolute magnitudes.

- Increase in shaft speed from 3.7 to 7.5 RPS has a similar effect upon load indices for the ducted and open propellers. At high pitch in thin ice, load indices are relatively insensitive to shaft speed, but at low pitch and in thick ice, the load indices display a moderate increase with increase in shaft speed. In general, results for the open propeller show a little less sensitivity with shaft speed than do those for the ducted propeller.

- Shaft loading indices for both the ducted and open propellers increase significantly with increase in ice thickness, the width of cut and forward speed.

- Increase in ice thickness from 50 mm to 100 mm, results in increases in direct ice loads of up to 300 - 400 % for both propeller systems.

- Increase in forward speed from 0.2 to 1.0 m/s, results in increases in direct ice loads of up to 400 % in 100 mm ice for both propeller systems.

- Increase in the width of cut from 200 mm to 400 mm, results in increases of up to 300 % in direct ice load indices for the ducted propeller, but of only 50 % for the open propeller.

- For the ducted propeller, reduction in pitch causes only a small increase in direct load indices in the higher loading situations . For the open propeller, torque loading shows the same trends, but thrust loading increases much more , by over 100 %.

- The maximum direct load indices, analyzed for the same parametric conditions, are very similar.
  For 200mm cut width, 1.0 m/s speed, low pitch in 100mm level ice, the relative magnitudes are: Thrust loading for the open propeller is 1.35 times that for the ducted propeller. Maximum torque loading for the open propeller is 1.05 times that for the ducted propeller. Mean torque loading for the open propeller is 1.3 times that for the ducted propeller.

6.6 Summary and Comparisons of Individual Blocks and Level Ice Tests

In order to make a comparison manageable between the individual ice block and level ice load indices, for both the ducted and open propellers, the summaries and comparisons in Sections 6.4 and 6.5 above are further summarized in Table 6.6.1.

This table presents:

- The broad trends in the results without reference to the numerous details discussed in the above sections. Approximate percentage effects of parameters are included.

- Specific maximum data in order that the relative magnitude of direct ice loads can be demonstrated clearly for the same or equivalent parametric conditions.

- The information in this table is based on the model test data as recorded and analyzed above. The model data will also be corrected for the dynamic magnification properties of the test equipment before subsequent comparison is made between full scale and equivalent model scale data. Correction for dynamic magnification will alter the numerical value of some of the data but is not expected to affect the trends and relativities demonstrated.

Table 6.6.1, demonstrates the following:

Individual Blocks

In thin, 50mm thick ice, load indices for the ducted and open propellers are similar.

In thicker, 100mm thick ice, load indices for the open propeller are 200% to 300% larger at bollard and 75% to 200% larger at 1 m/s than for the ducted propeller.

The dominant parameter causing this is ice thickness, the differences in the parametric trends between the open and ducted propellers for all other parameters being relatively small in comparison.

This ice thickness effect continues dramatically for the open propeller for ice thicknesses above 100mm. The same condition has not been tested for the ducted propeller.

Level Ice

In thin, 50mm, level ice, load indices for the ducted propeller are approximately 50% higher than for the open propeller. In thicker, 100mm, level ice, the direct ice load indices for the open propeller are 5% to 30% larger than for the ducted propeller.
The numerical reason for this small overall shift in relative magnitudes lies in the fact that there is no single parameter that affects the ducted and open propellers in a significantly different way.

The physical reason for the above is as follows.

Individual Blocks versus Level Ice

The maximum direct load indices for the open propeller in comparable conditions of low pitch, 1.0 m/s, 100mm thick ice and 200mm blocks or cut width, increase by only 15% to 30% as the conditions change from individual blocks to a continuous stream of blocks. Clearly, the open propeller does not slow down the arriving blocks and mills them one by one as they arrive in a virtually consecutive fashion. There is every indication that multiple milling of blocks does not occur. This also suggests that the analysis, using premilled data for single blocks, is correct for the level ice case. It also indicates that design loads for the open propeller can be based essentially on individual block milling forces, the critical element thereby becoming the design block thickness and size.

The maximum direct load indices for the ducted propeller in comparable conditions of low pitch, 1.0 m/s, 100mm thick ice and 200mm blocks or cut width, increase by 100% to 200% as the conditions change from individual blocks to a continuous stream of blocks. These data confirm the visual observations that individual blocks are slowed down by the ducted propeller. The total amount of work done in milling each block is subsequently spread over a longer time interval than the arrival interval between successive blocks in the continuous stream of blocks. Milling thereby takes place with more than one block at a time, giving rise to the increased direct load indices for the ducted propeller in the level ice situation. The data analyzed to date show that design loads for the ducted propeller should therefore be based on a multiple milling condition. For the ice thicknesses investigated so far, it would appear that this results in maximum levels of two to three times the maximum direct ice load indices for individual blocks. However, as with the comparison of direct ice loads between the ducted and open propellers, the magnitudes of the thrust and torque loads should be investigated in thicker ice conditions in order to confirm these trends and provide more specific design information for high ice class conditions.

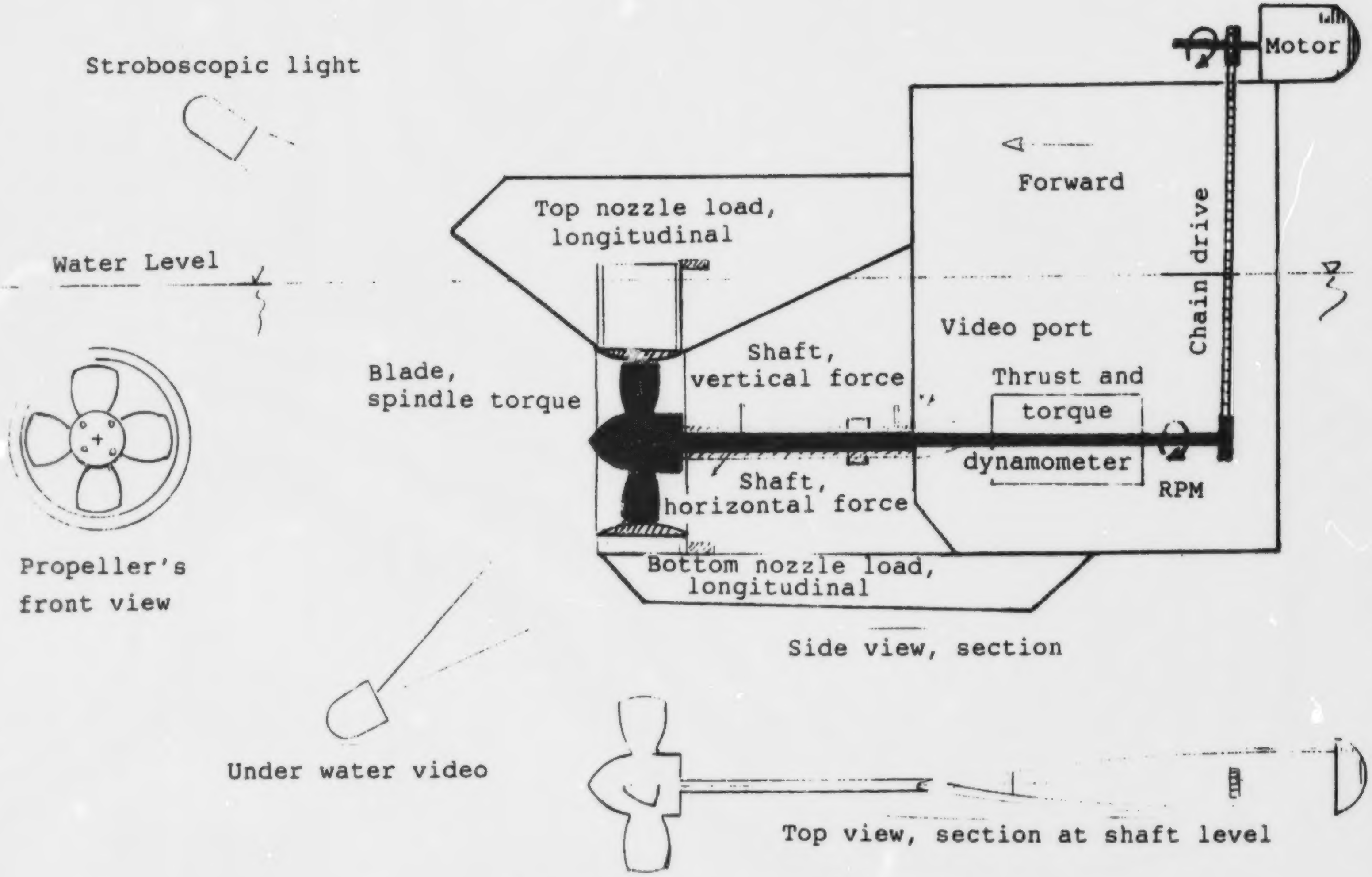
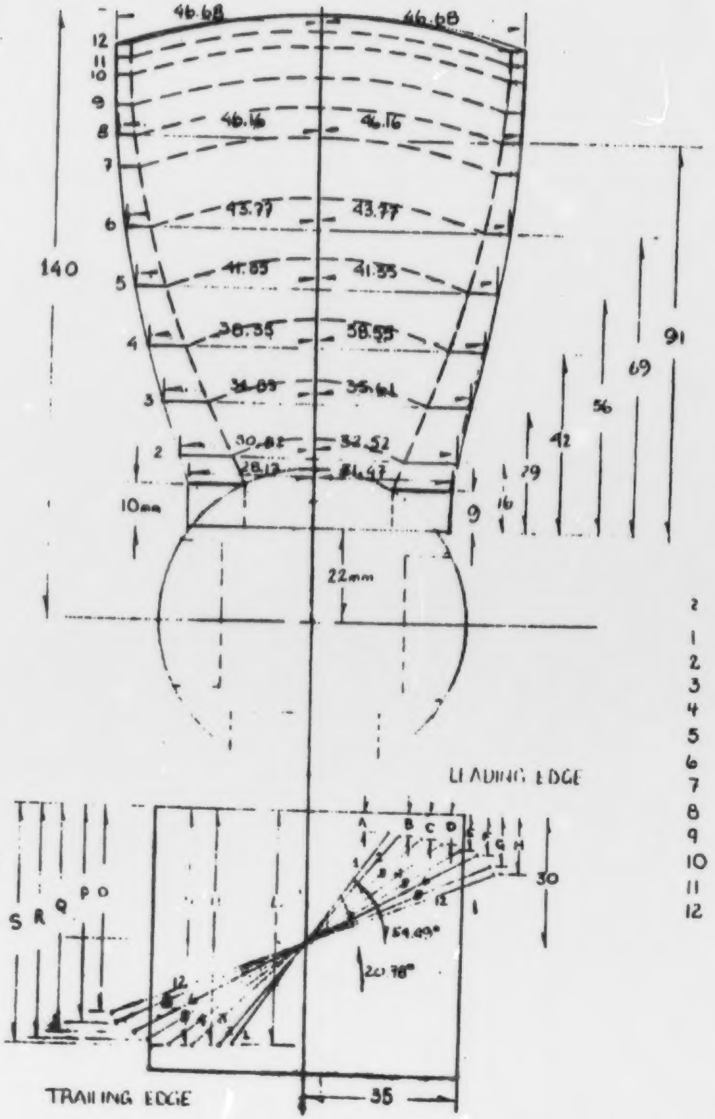


Figure 2.1. Schematic presentation of propulsion model test vessel.

RIGHT HAND TURNING PROPELLER



LETTER	r	DIMENSION (mm)
A	1	4.28
B	2	5.02
C	3	5.65
D	4	6.69
E	5	7.89
F	6	9.14
G	8	11.18
H	12	13.44
L	1	52.93
M	2	53.37
N	3	53.82
O	4	53.19
P	5	52.11
Q	6	50.86
R	8	48.82
S	12	46.56

r	RADIUS	ANGLE (β) (DEG)	TRAIL (β)	LEAD (β)	TRAIL (A)	LEAD (A)
1	35	54.49	22.93	25.62	28.17	31.47
2	42	50.18	23.67	24.98	30.82	32.52
3	56	43.15	23.82	24.35	34.83	35.61
4	70	37.20	23.19	23.31	38.35	38.55
5	84	32.32	22.11	22.11	41.35	41.35
6	98	28.47	20.86	20.86	43.17	43.77
7	112	25.38	19.51	19.51	45.51	45.51
8	119	24.06	18.82	18.82	46.16	46.16
9	126	22.87	18.10	18.10	46.58	46.59
10	133	21.78	17.33	17.33	46.71	46.11
11	136.5	21.27	16.43	16.43	46.68	46.68
12	140	20.78	16.56	16.56	46.68	46.68

NOTE: ALL DIMENSIONS ARE IN MILLIMETERS

Figure 2.2. Design of Propeller for Model Tests.

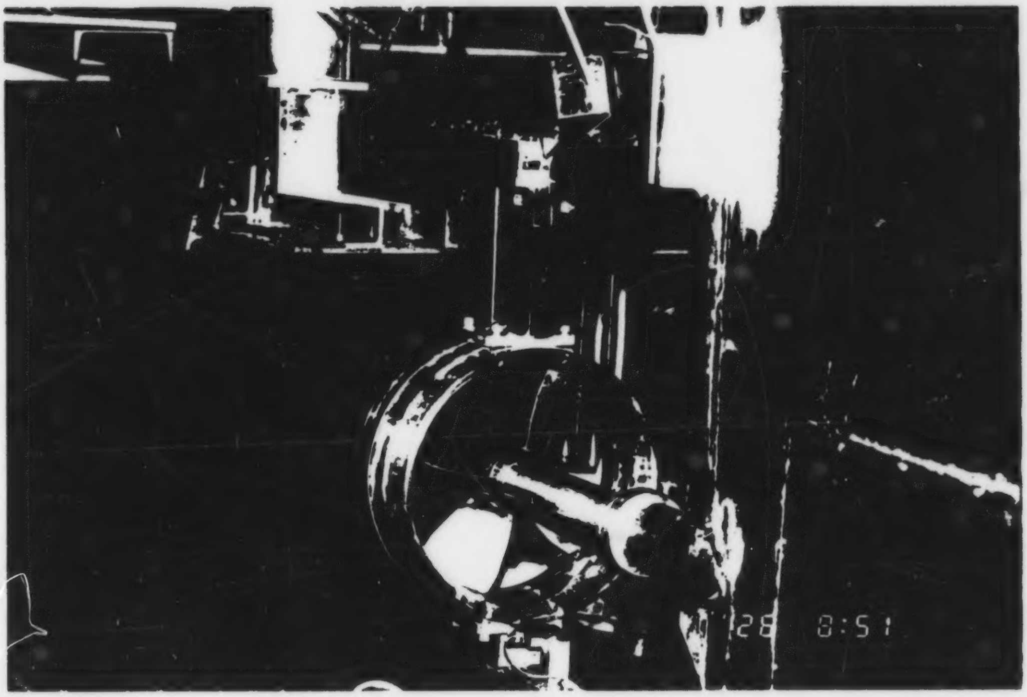


Figure 2.3 Model Test Equipment.

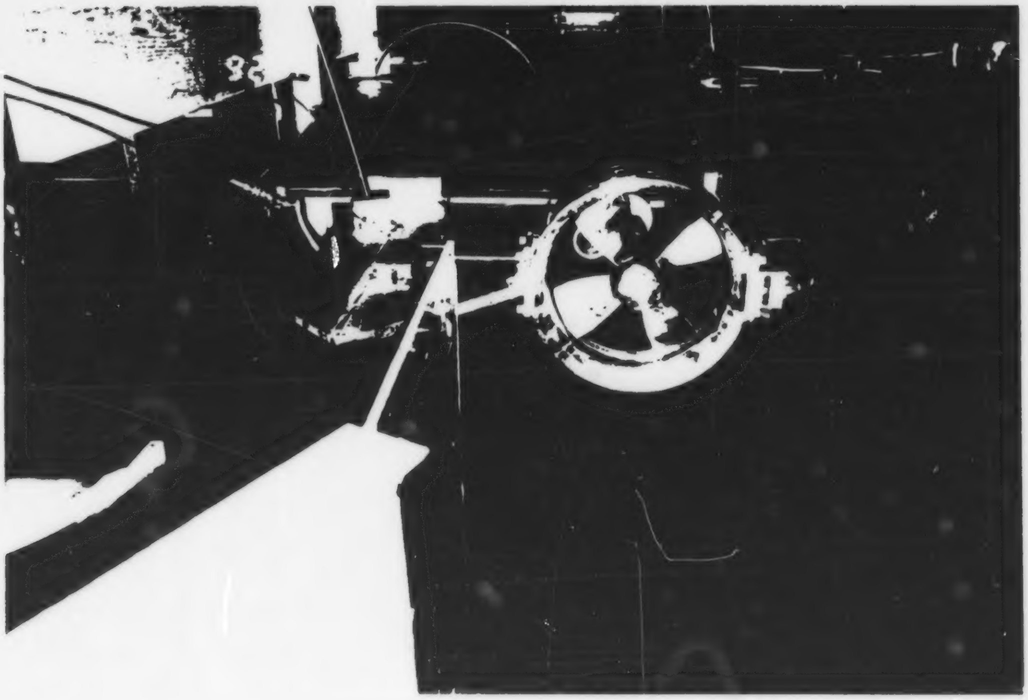


Figure 2.4 Model Test Equipment.

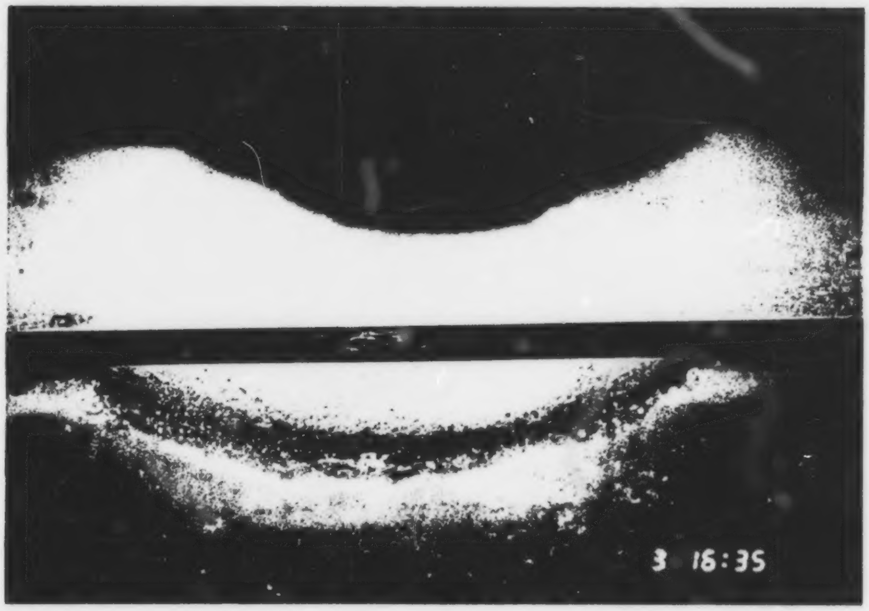


Figure 3.1 Milled Ice Block, 35 % blade length cut depth

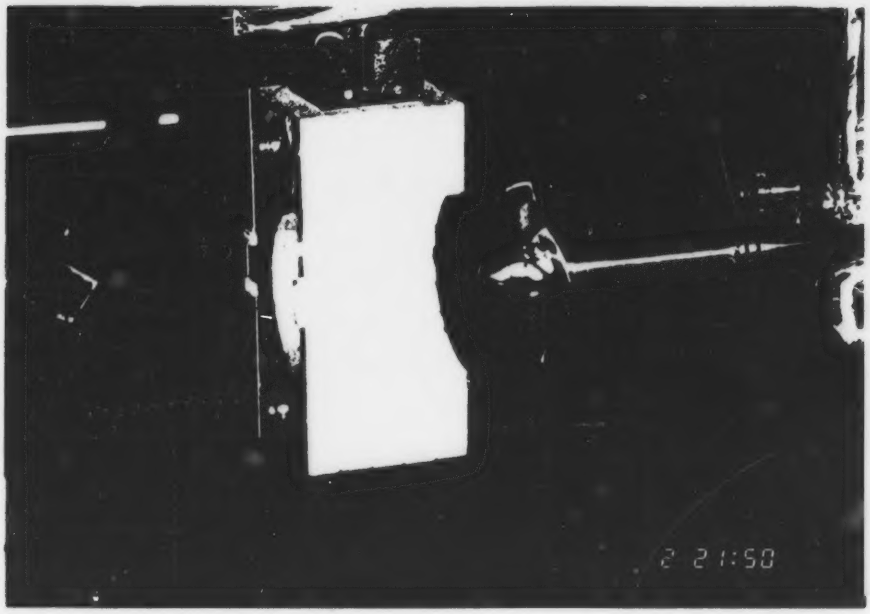


Figure 3.2 Precut Test Block.

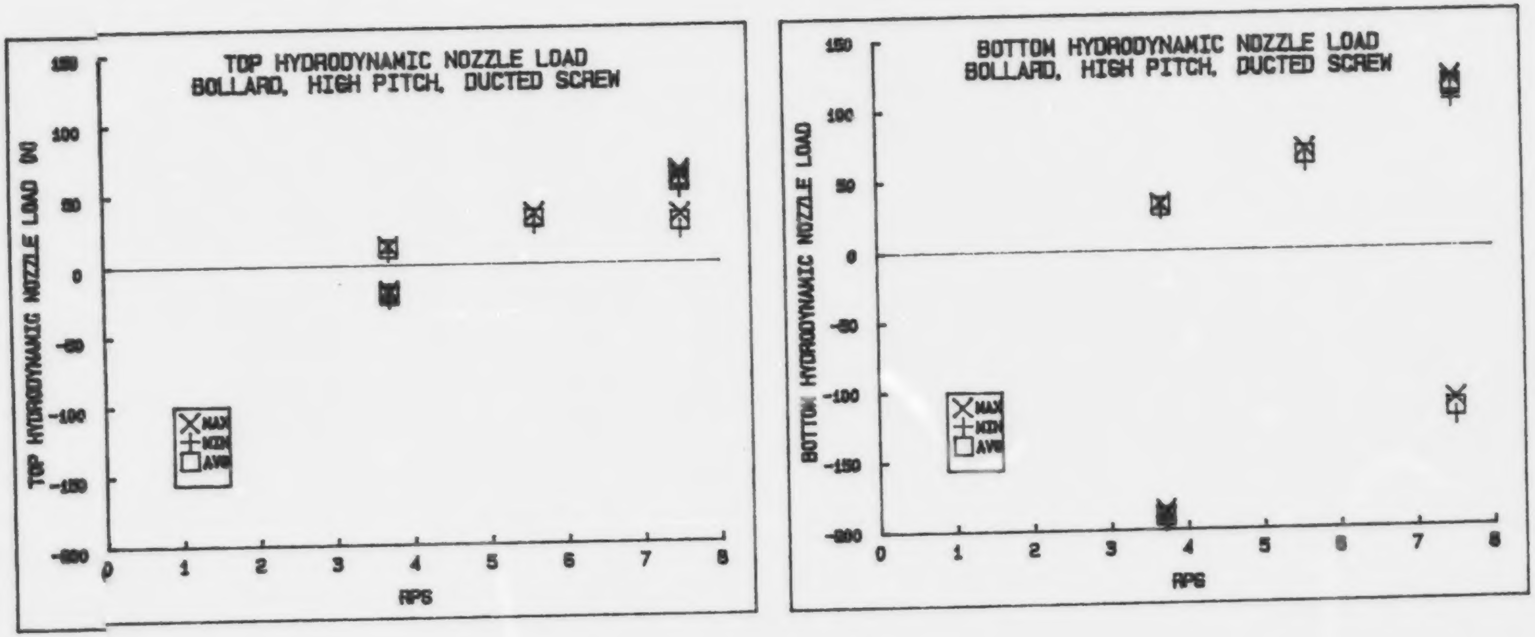


FIGURE 4.2.1 THE EFFECT OF RPS ON HYDRODYNAMIC NOZZLE LOAD (HIGH PITCH)

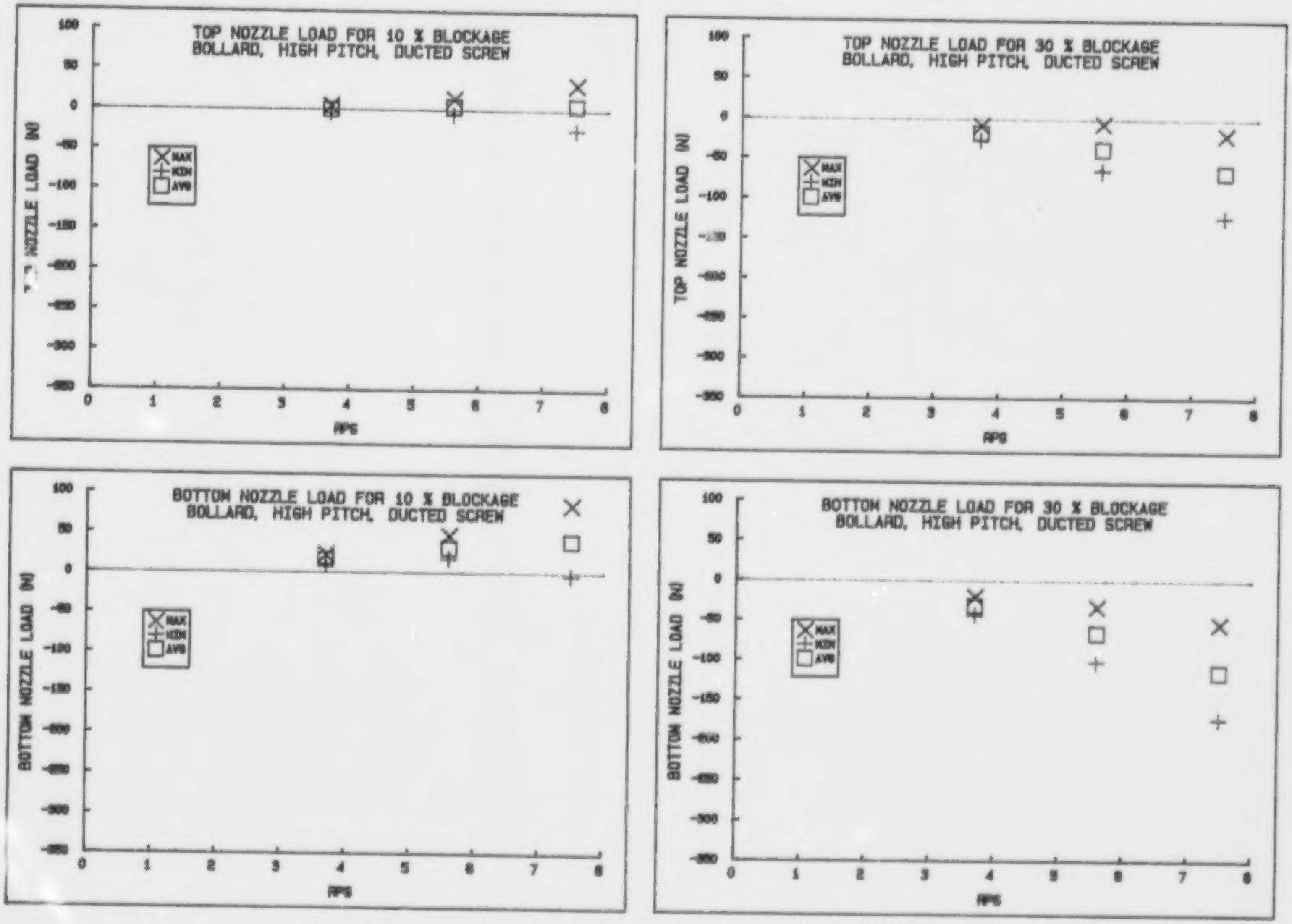


FIGURE 4.2.2 THE EFFECT OF RPS ON NOZZLE LOAD UNDER BLOCKAGE CONDITIONS AT HIGH PITCH

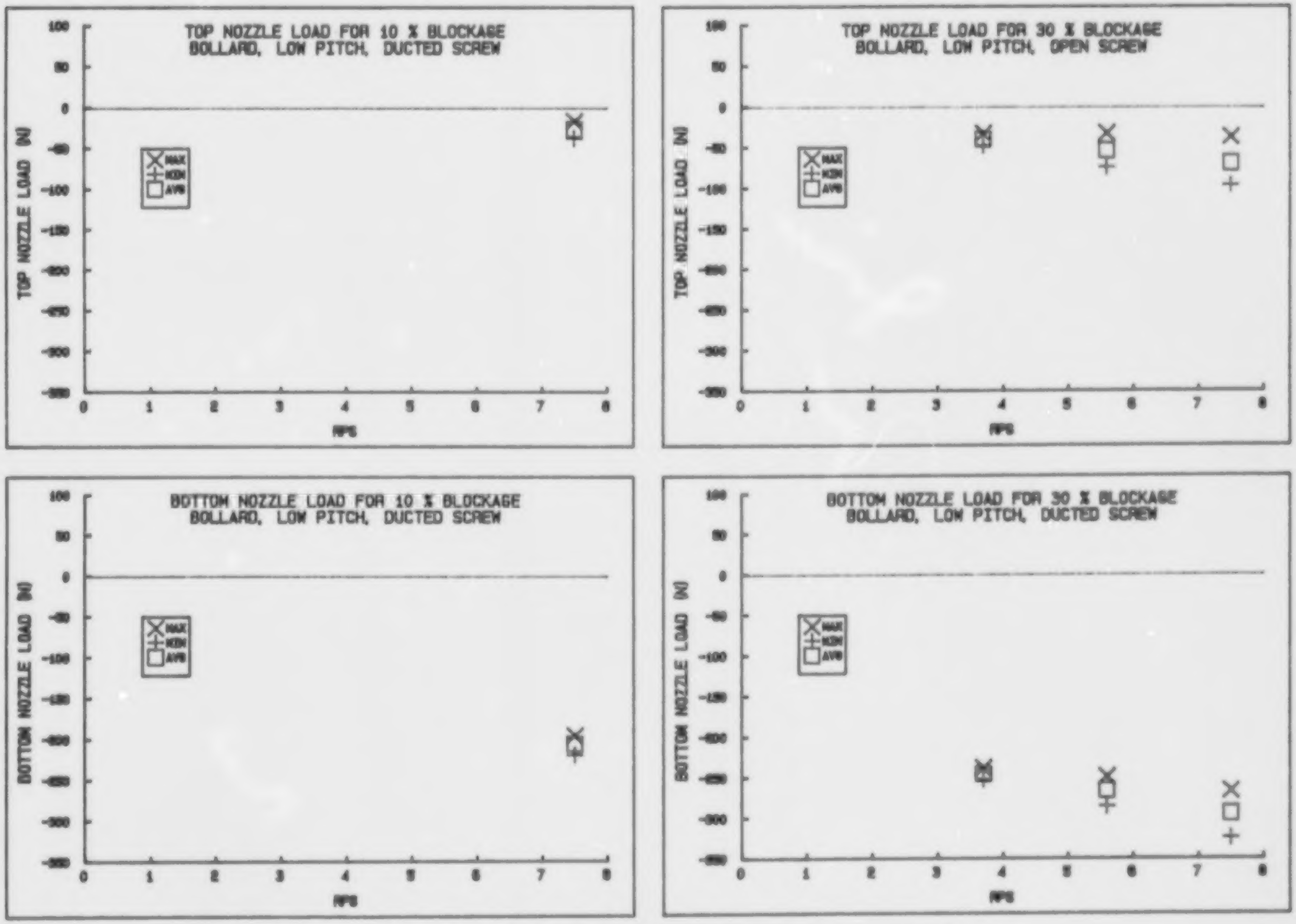


FIGURE 4.2.3 THE EFFECT OF RPS ON NOZZLE LOAD UNDER BLOCKAGE CONDITIONS AT LOW PITCH

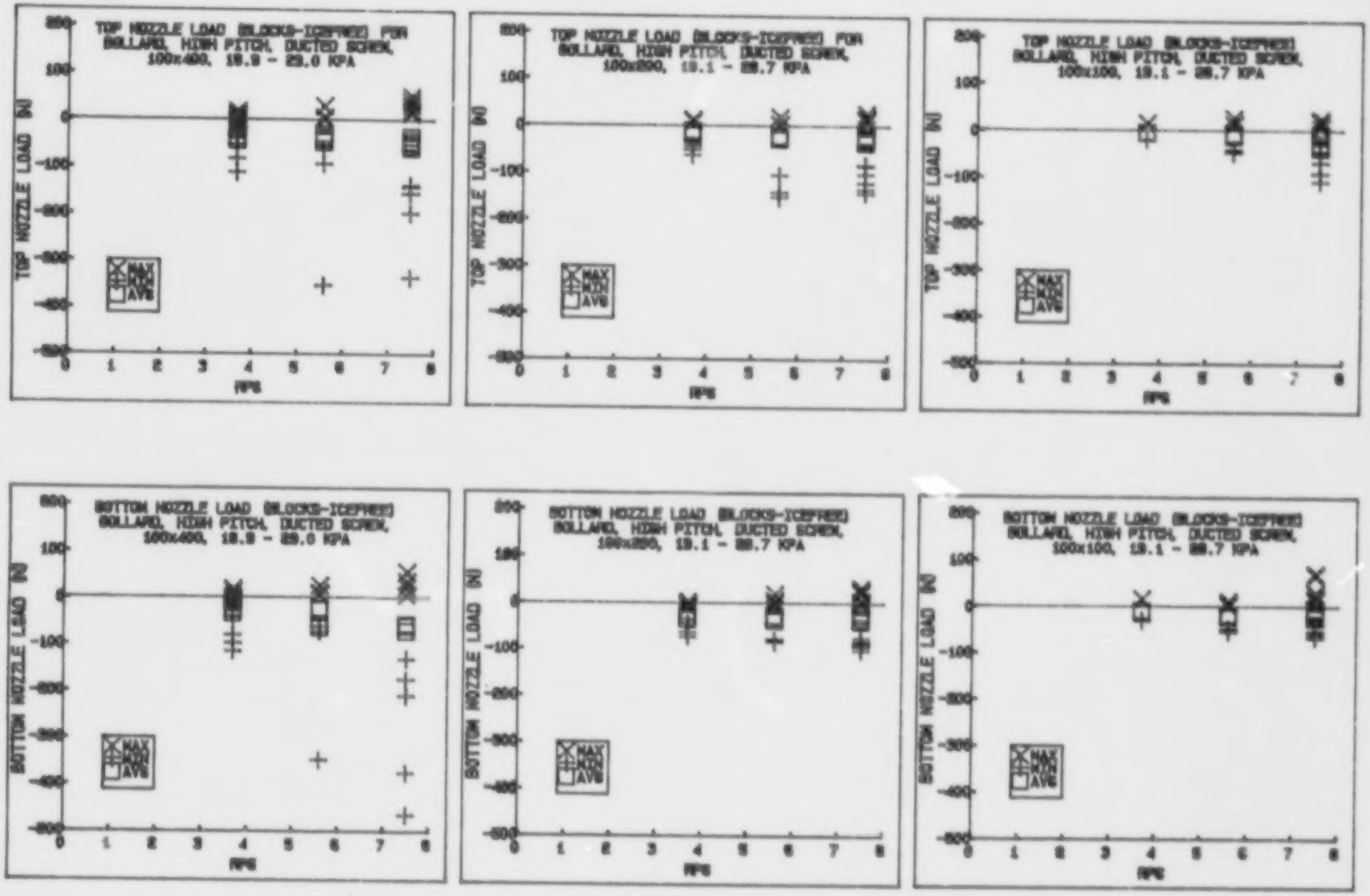


FIGURE 4.2.4 THE EFFECT OF RPS ON NOZZLE LOAD FOR ALL BLOCK SIZES, HIGH PITCH

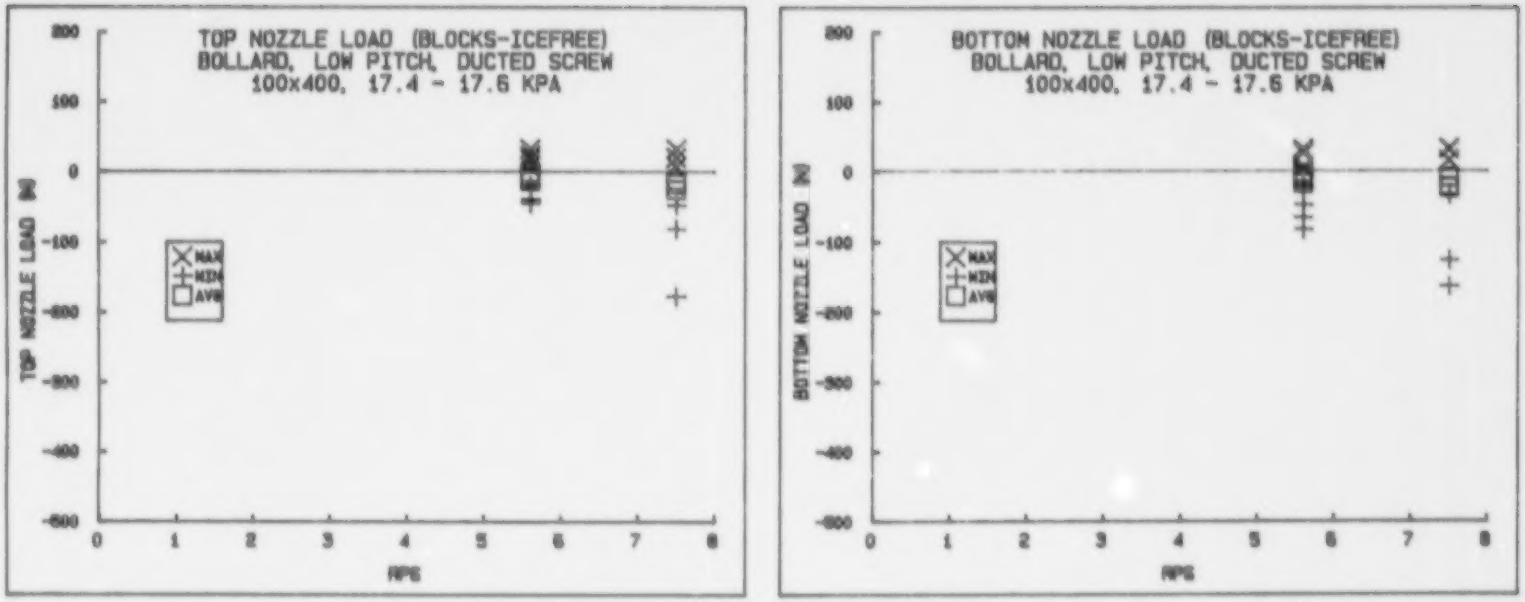


FIGURE 4.2.5 THE EFFECT OF RPS ON NOZZLE LOAD FOR LOW PITCH, LARGEST BLOCKS

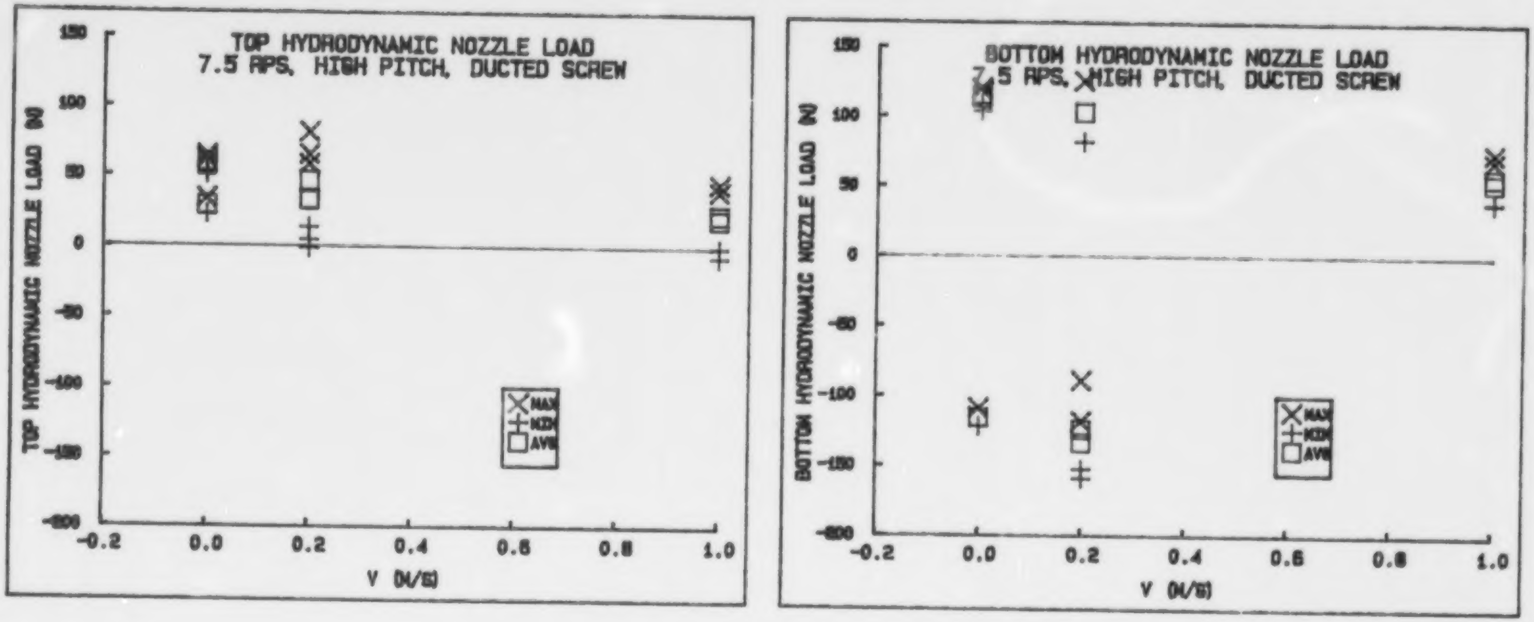


FIGURE 4.2.6 THE EFFECT OF VELOCITY ON HYDRODYNAMIC NOZZLE LOAD (HIGH PITCH)

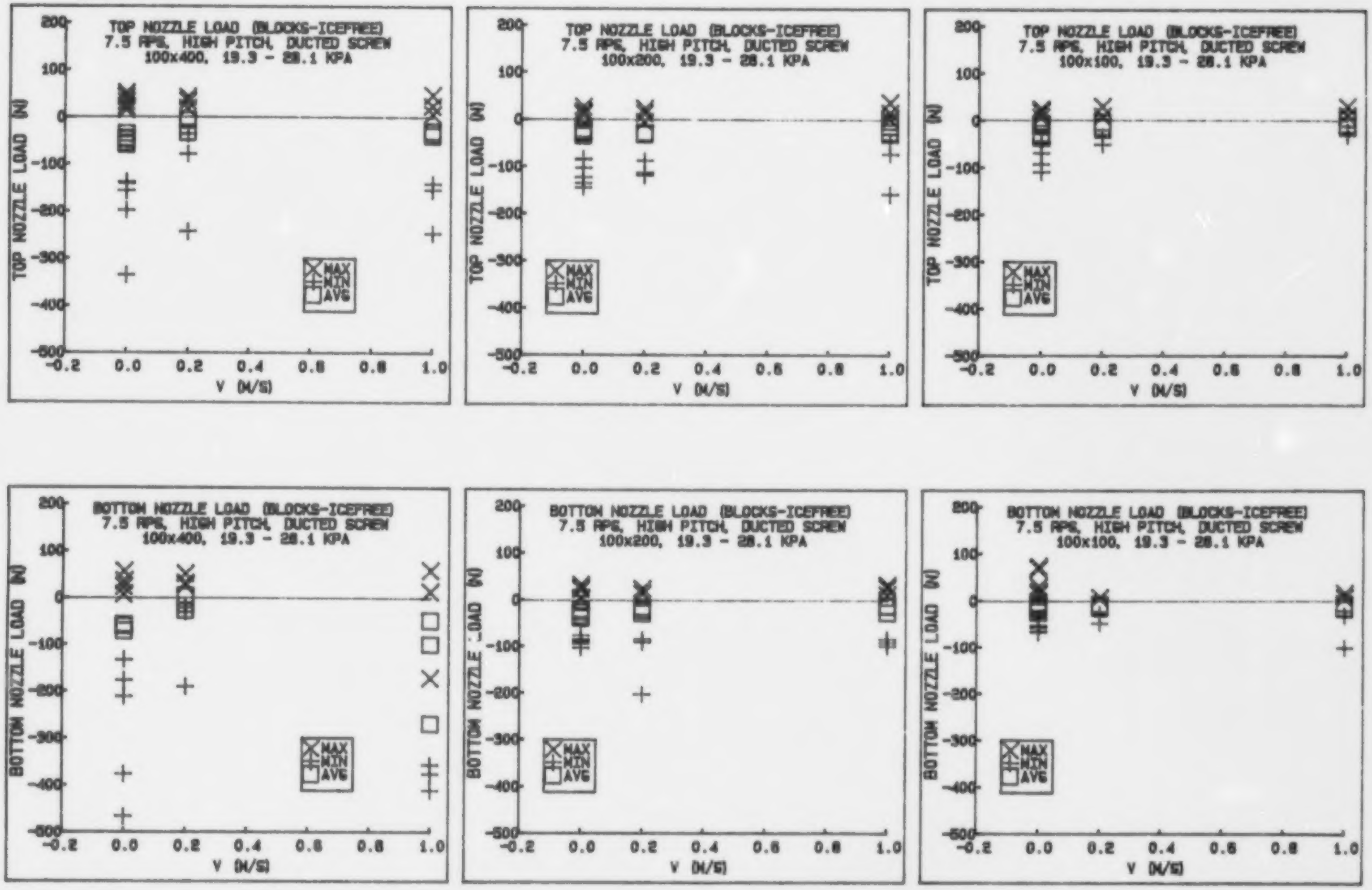


FIGURE 4.2.7 THE EFFECT OF VELOCITY ON NOZZLE LOAD FOR ALL BLOCK SIZES, HIGH PITCH

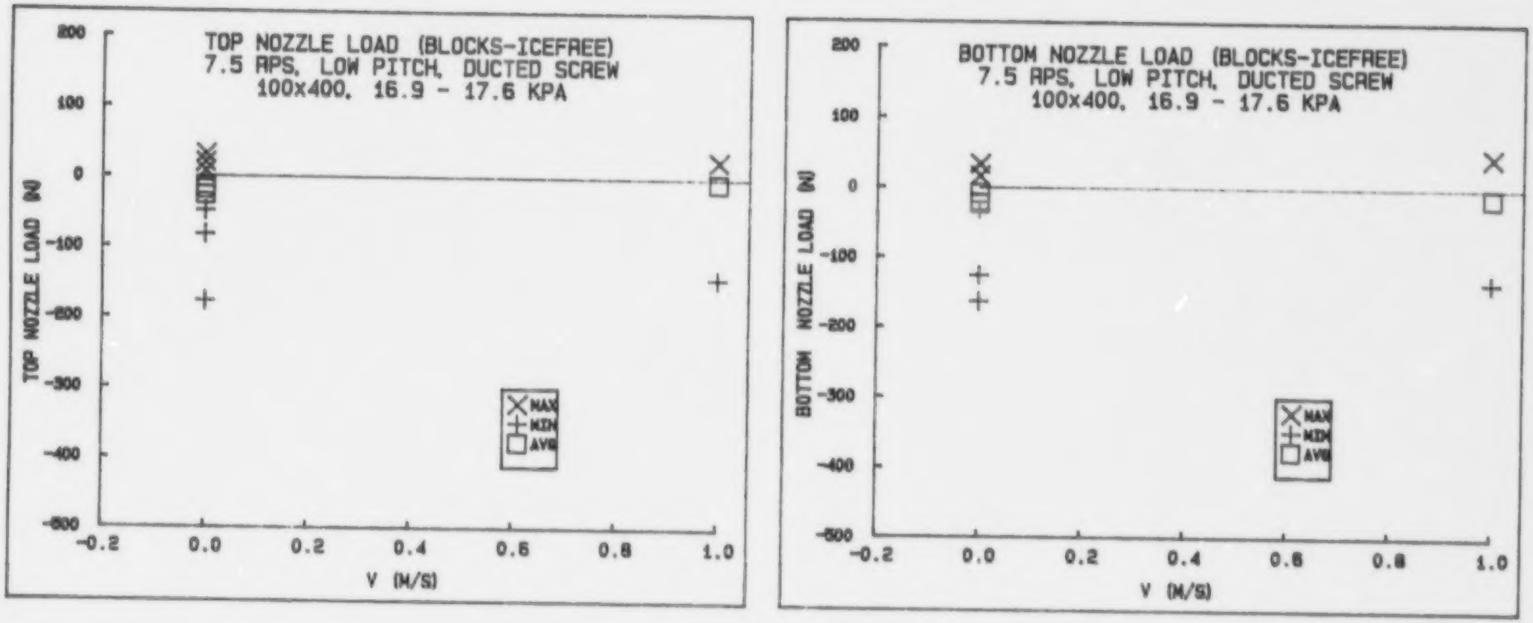


FIGURE 4.2.8 THE EFFECT OF VELOCITY ON NOZZLE LOAD FOR LOW PITCH, LARGEST BLOCKS

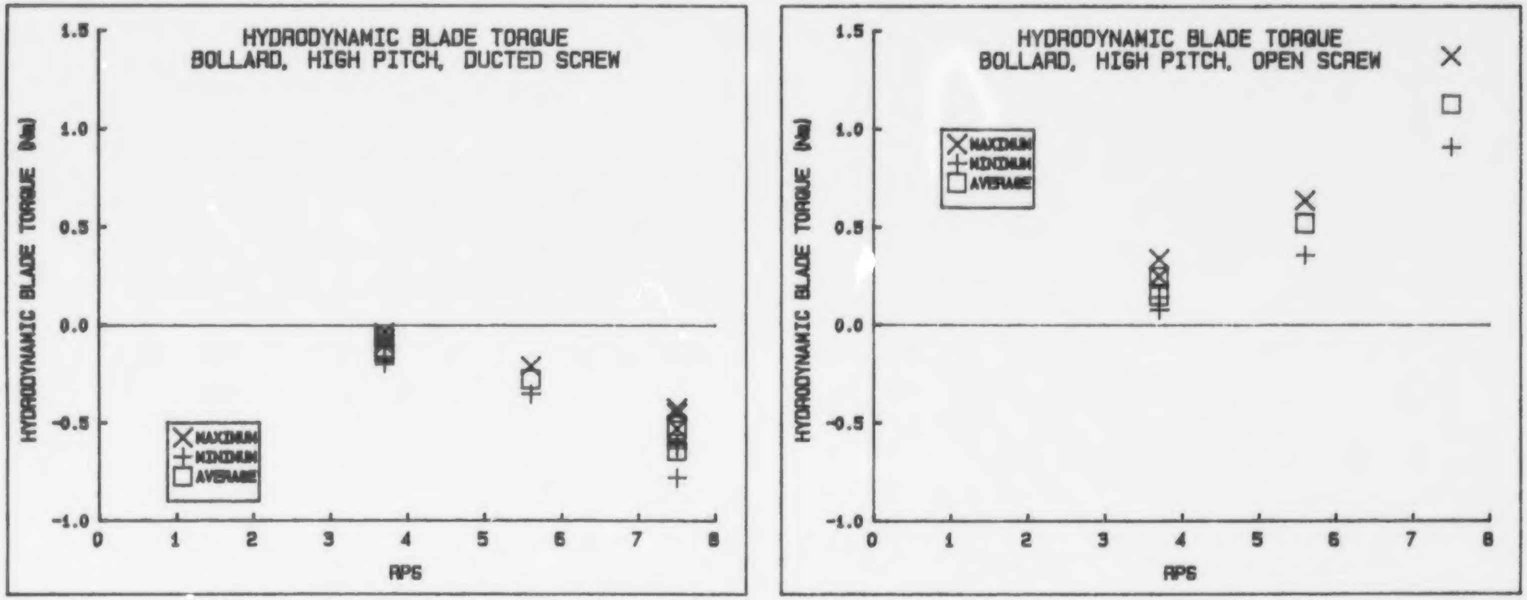


FIGURE 4.3.1 THE EFFECT OF RPS ON HYDRODYNAMIC BLADE TORQUE, HIGH PITCH

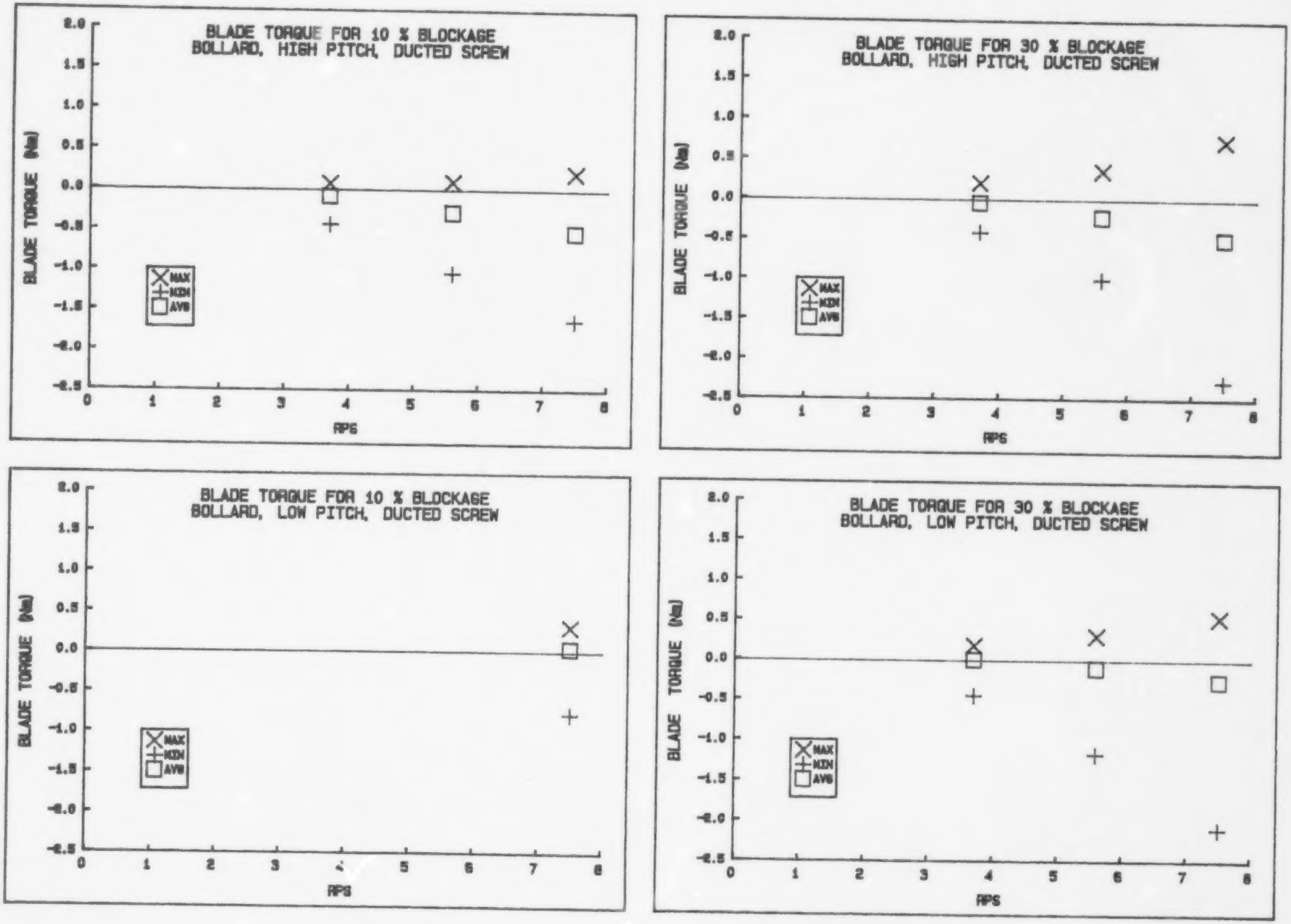
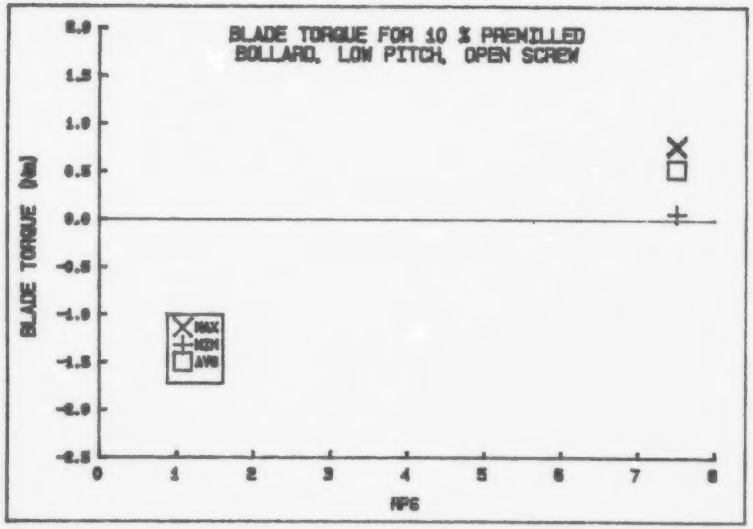
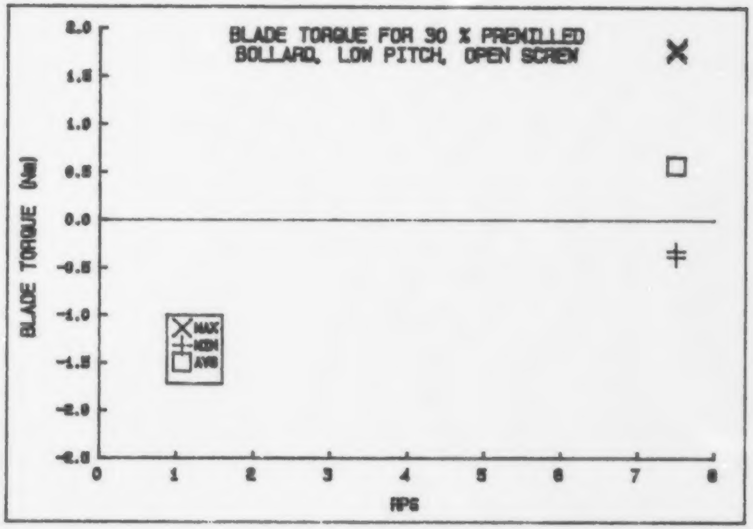


FIGURE 4.3.2 THE EFFECT OF RPS ON BLADE TORQUE FOR BLOCKAGE CONDITIONS





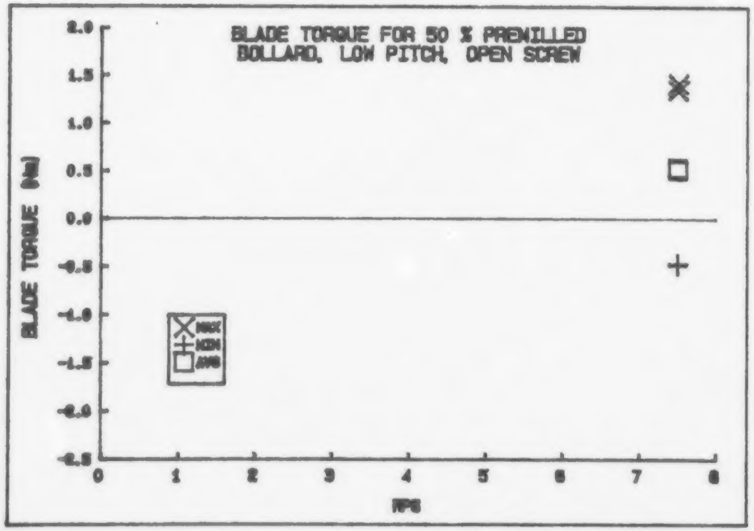


FIGURE 4.3.3 THE EFFECT OF RPS ON BLADE TORQUE FOR PREMILLED

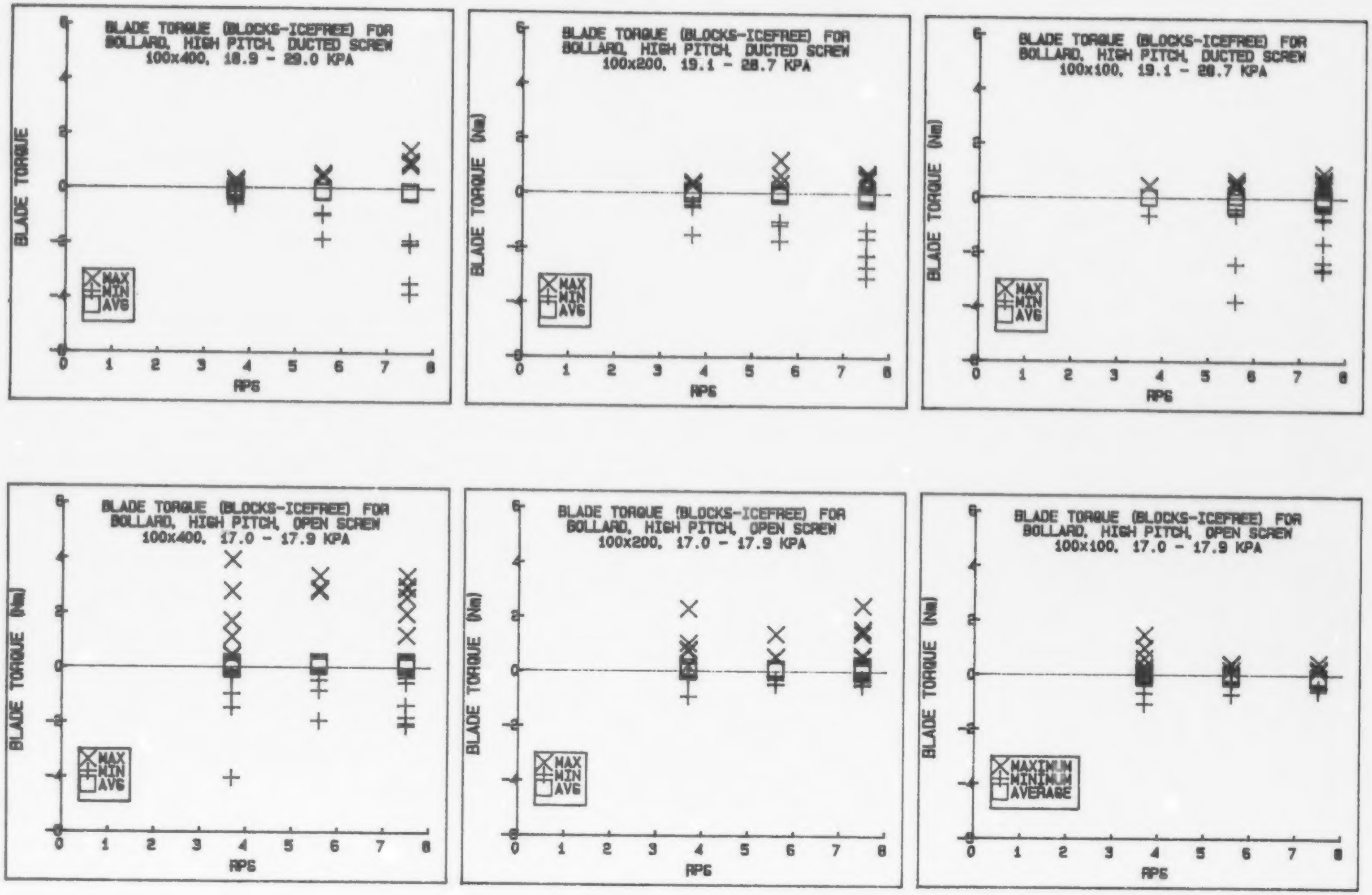


FIGURE 4.3.4 THE EFFECT OF RPS ON BLADE TORQUE FOR ALL BLOCK SIZES, HIGH PITCH

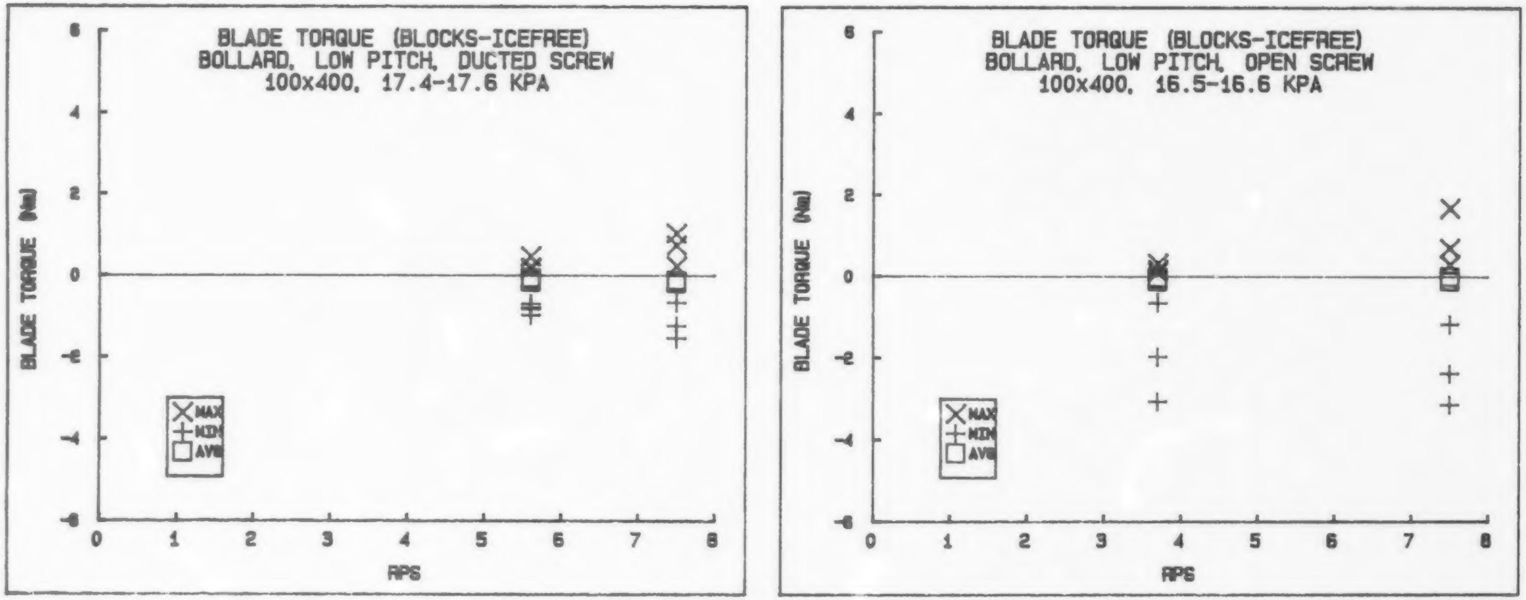


FIGURE 4.3.5 THE EFFECT OF RPS ON BLADE TORQUE FOR LOW PITCH, LARGEST BLOCKS

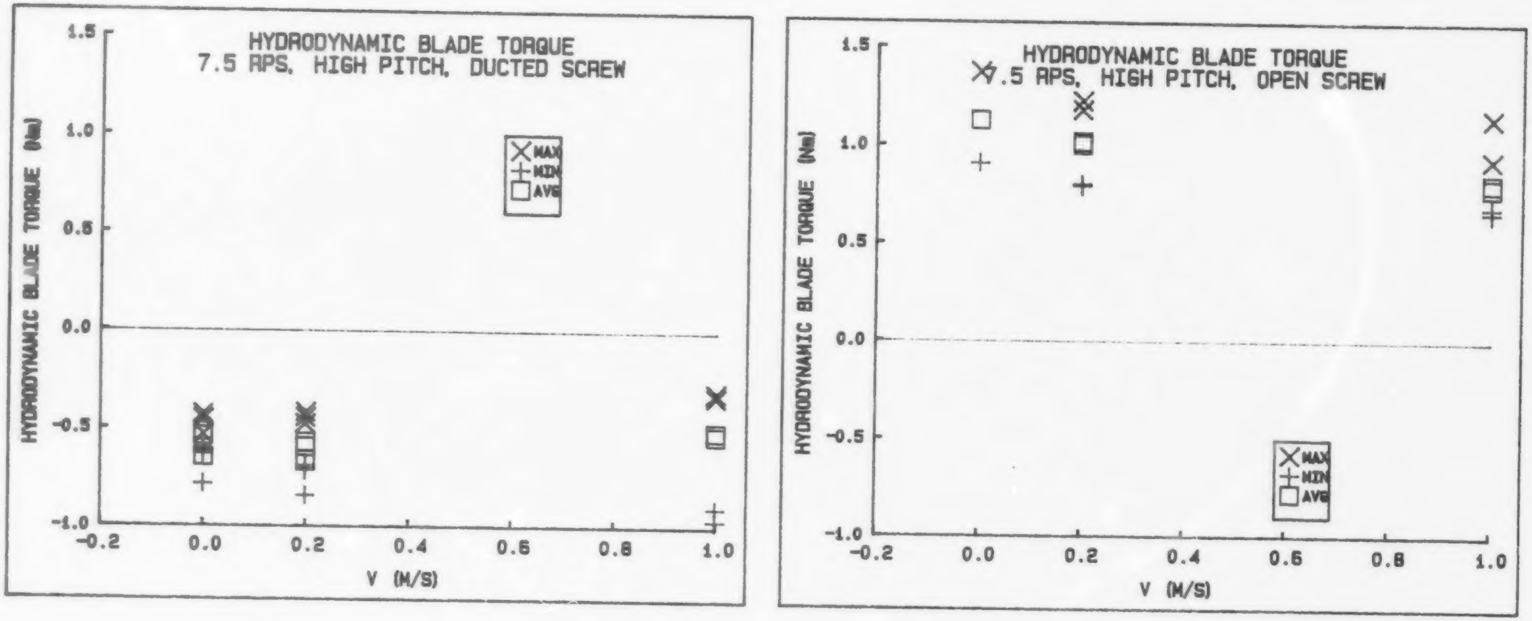


FIGURE 4.3.6 THE EFFECT OF VELOCITY ON HYDRODYNAMIC BLADE TORQUE, HIGH PITCH

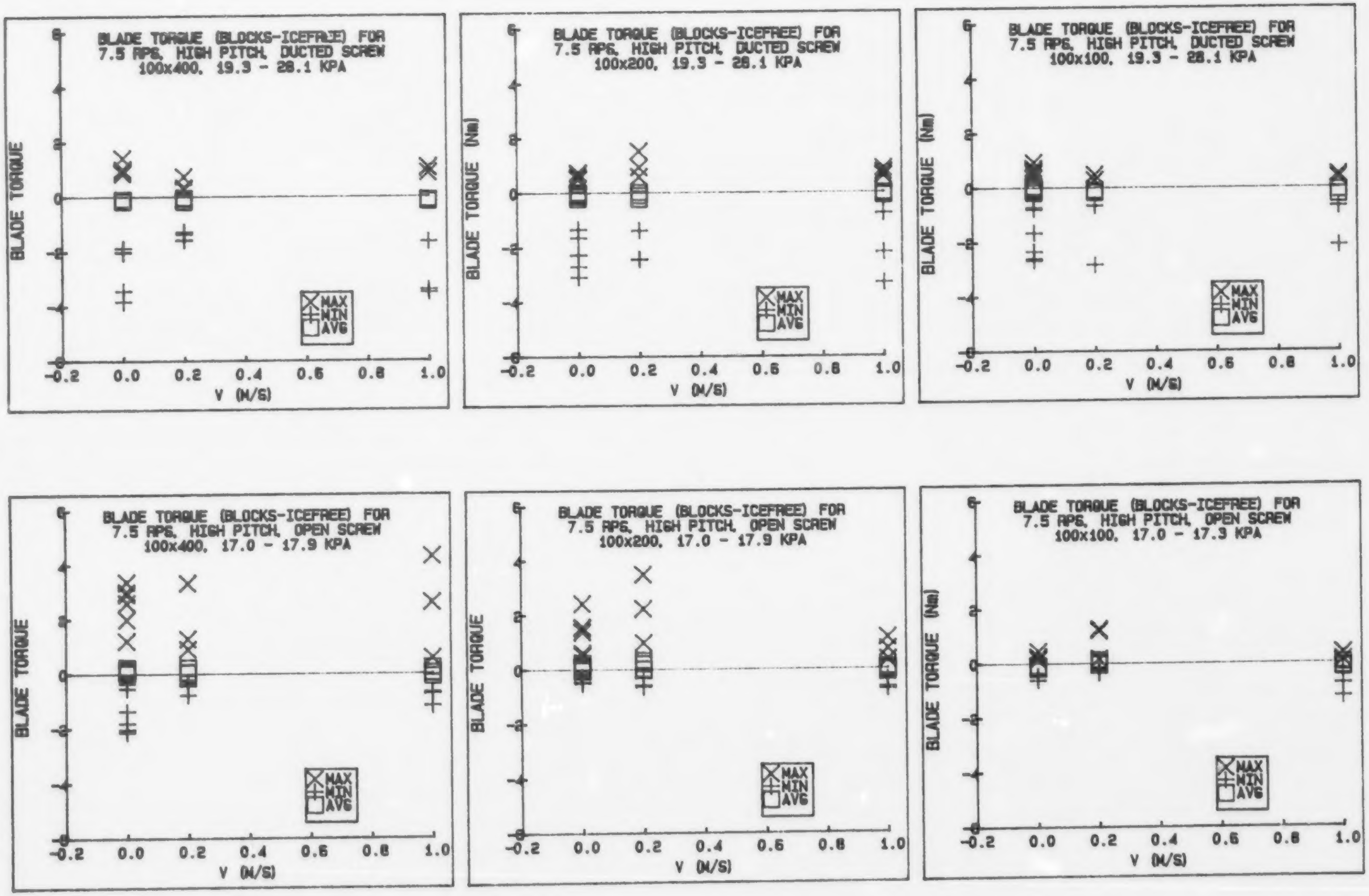


FIGURE 4.3.7 THE EFFECT OF VELOCITY ON BLADE TORQUE, ALL BLOCK SIZES

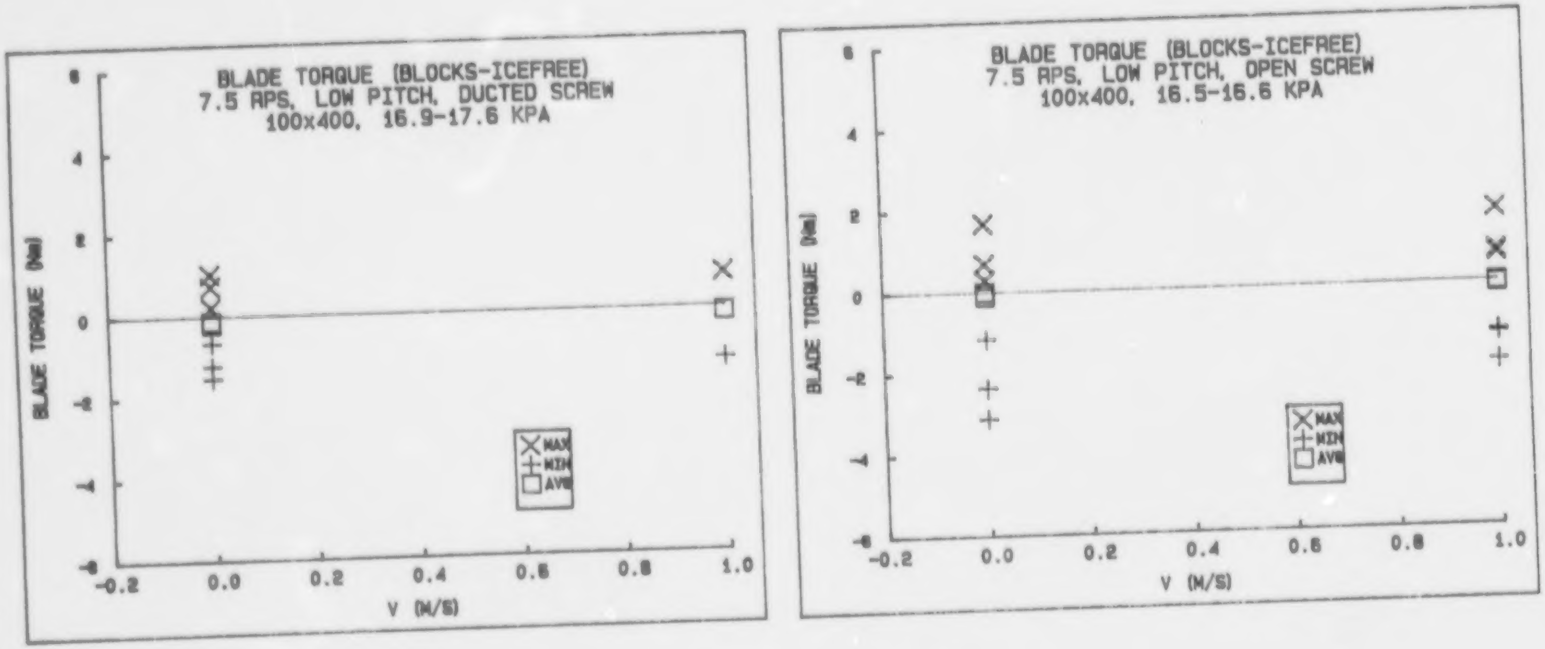


FIGURE 4.3.8 THE EFFECT OF VELOCITY ON BLADE TORQUE FOR LOW PITCH, LARGEST BLOCKS

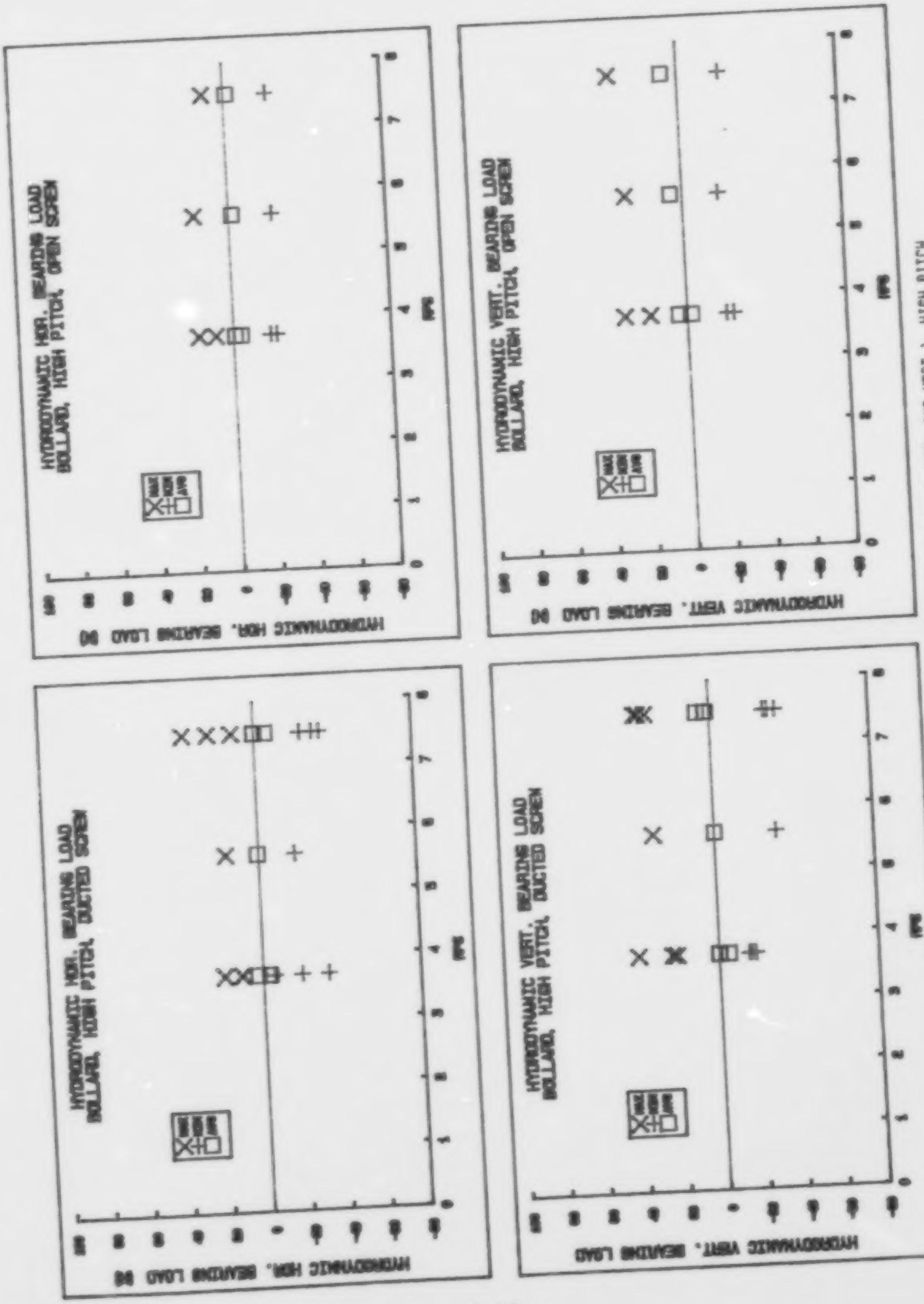


FIGURE 4.4.1 THE EFFECT OF RPS ON HYDRODYNAMIC BEARING LOAD (HOR. AND VERT.), HIGH PITCH

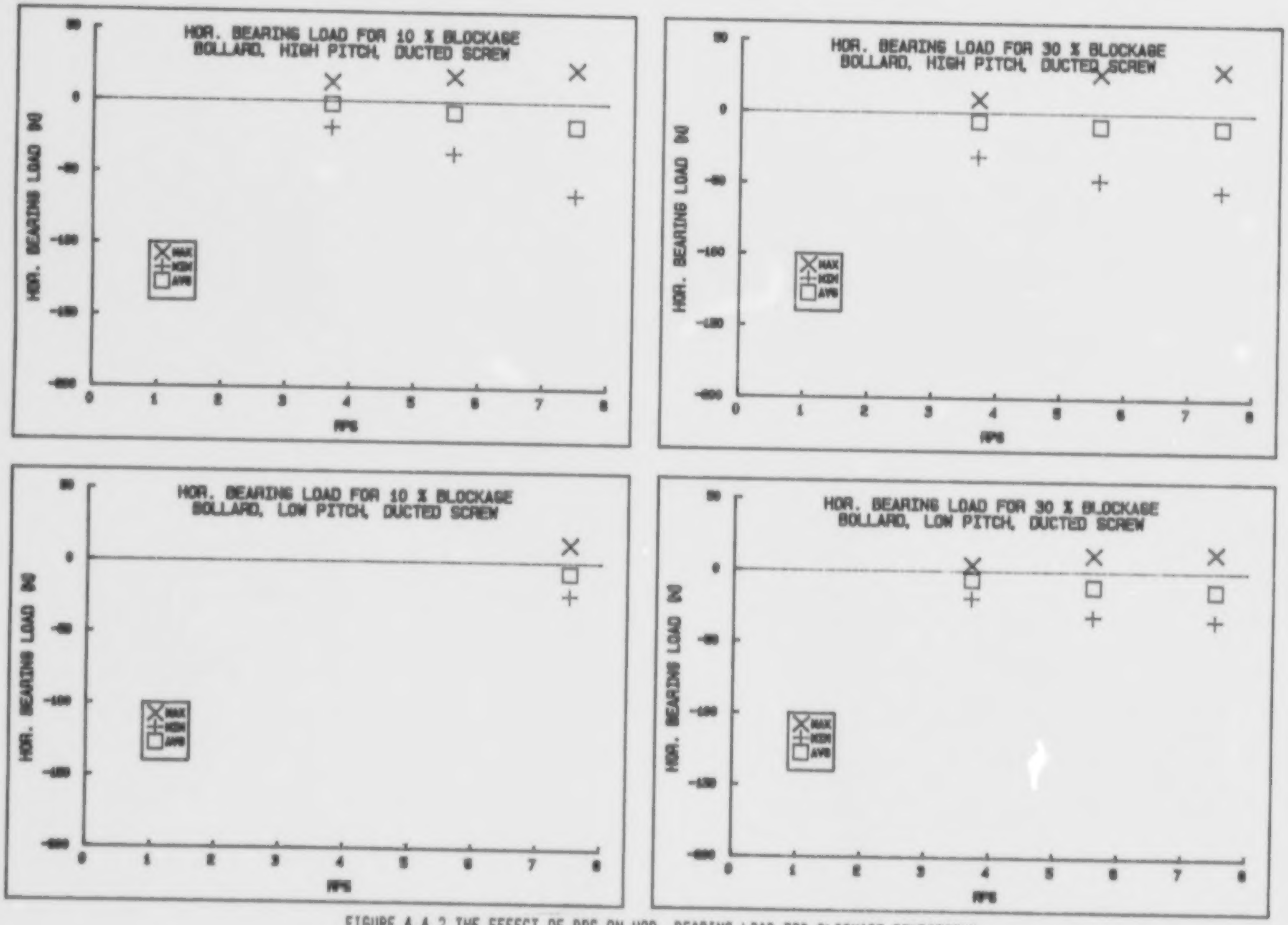


FIGURE 4.4.2 THE EFFECT OF RPS ON HOR. BEARING LOAD FOR BLOCKAGE CONDITIONS

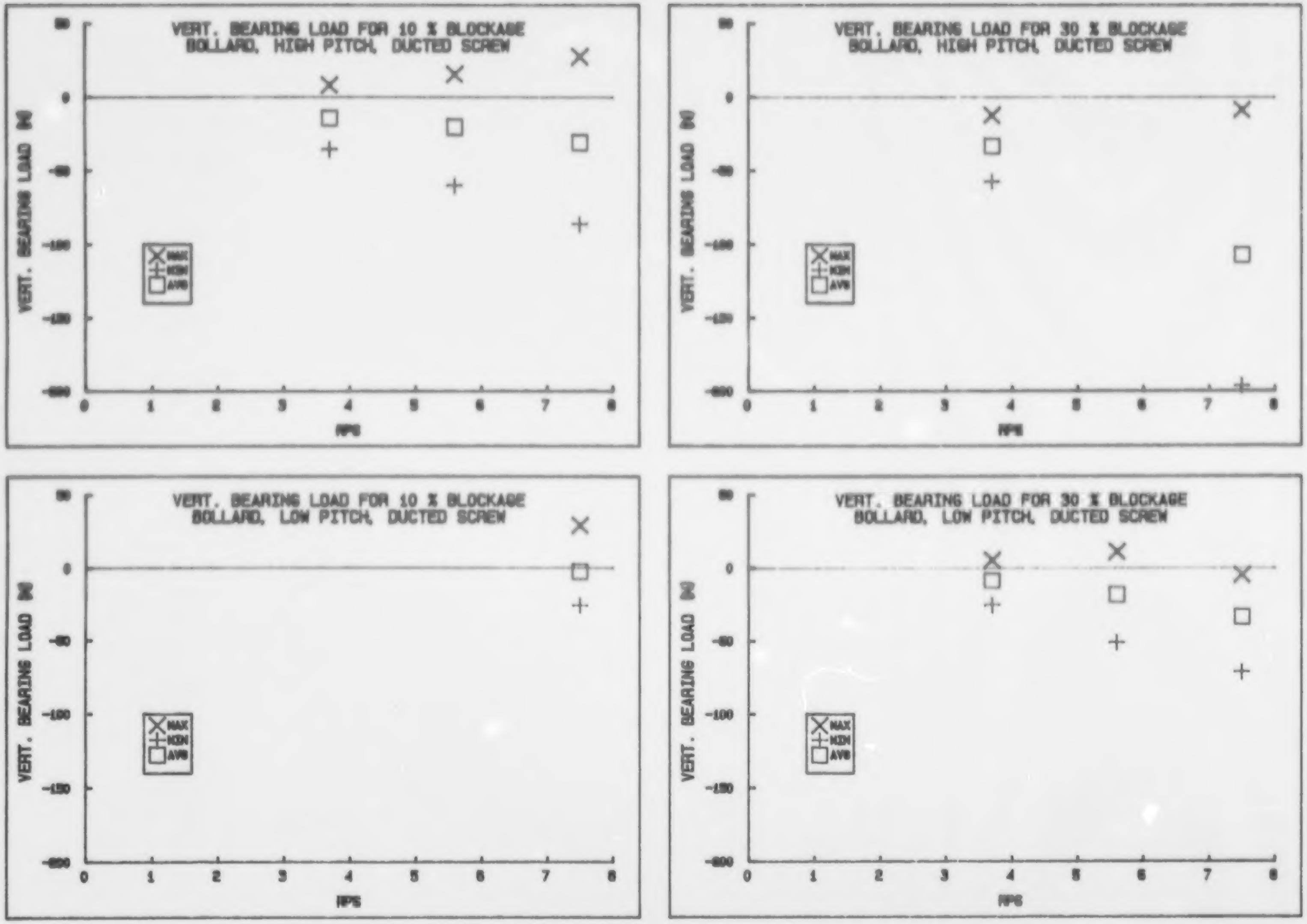


FIGURE 4.4.3 THE EFFECT OF RPS ON VERT. BEARING LOAD FOR BLOCKAGE CONDITIONS

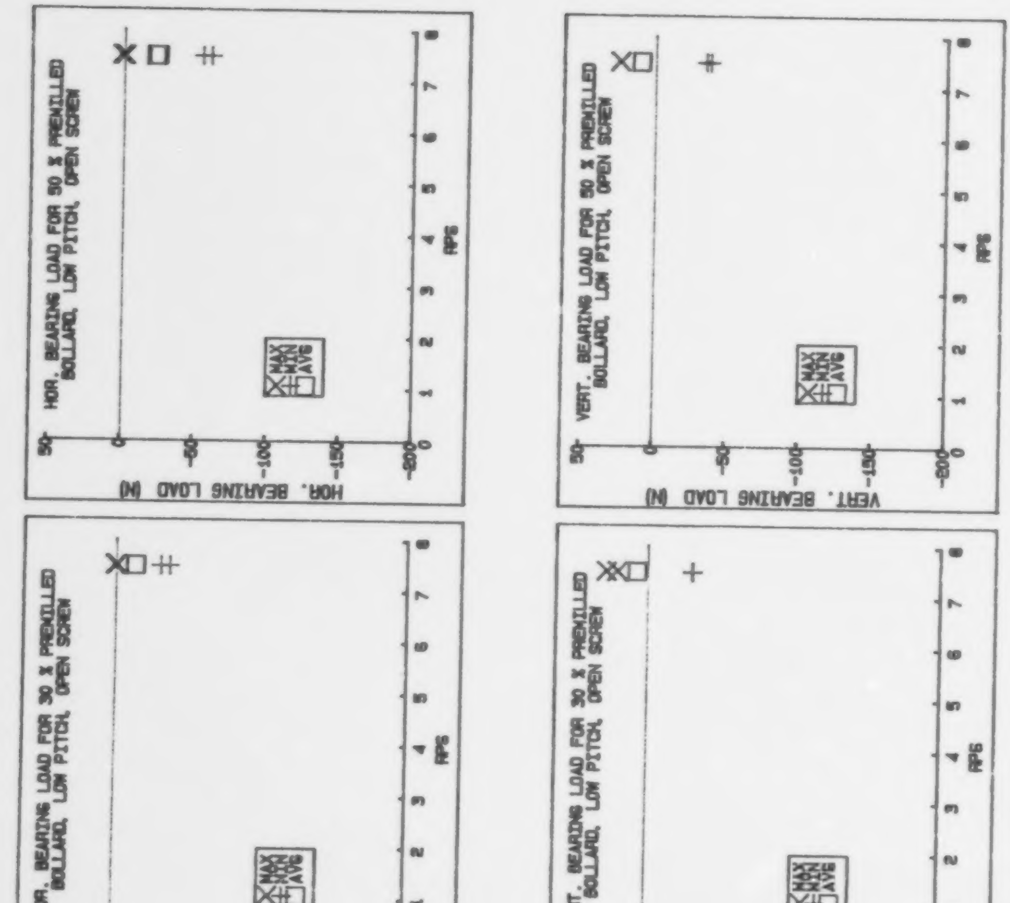


FIGURE 4.4.4 THE EFFECT OF RPS ON BEARING LOAD (HOR. AND VERT.) FOR PREMILLED

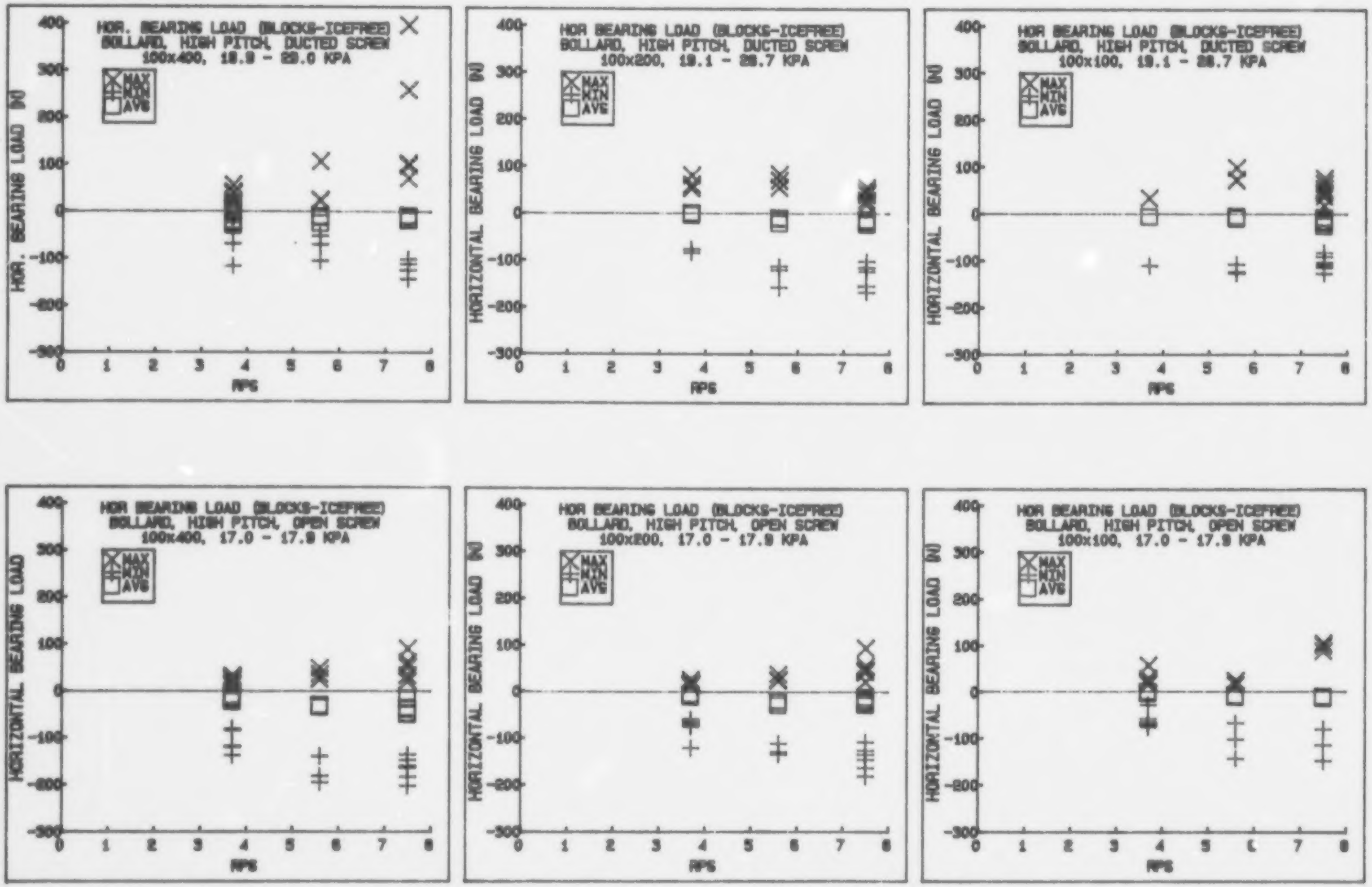


FIGURE 4.4.5 THE EFFECT OF RPS ON HOR. BEARING LOAD FOR ALL BLOCK SIZES, HIGH PITCH

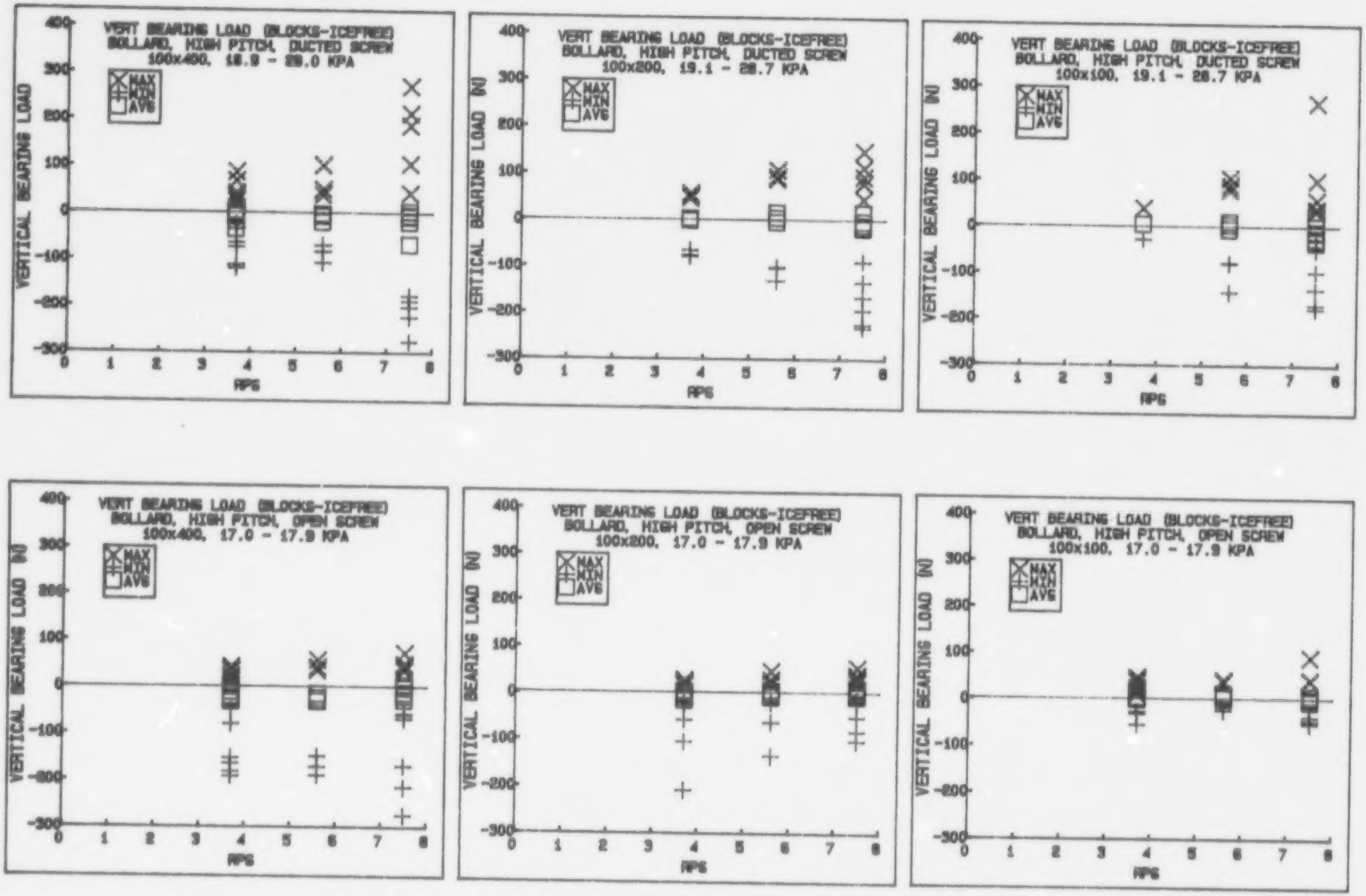


FIGURE 4.4.6 THE EFFECT OF RPS ON VERT. BEARING LOAD FOR ALL BLOCK SIZES, HIGH PITCH

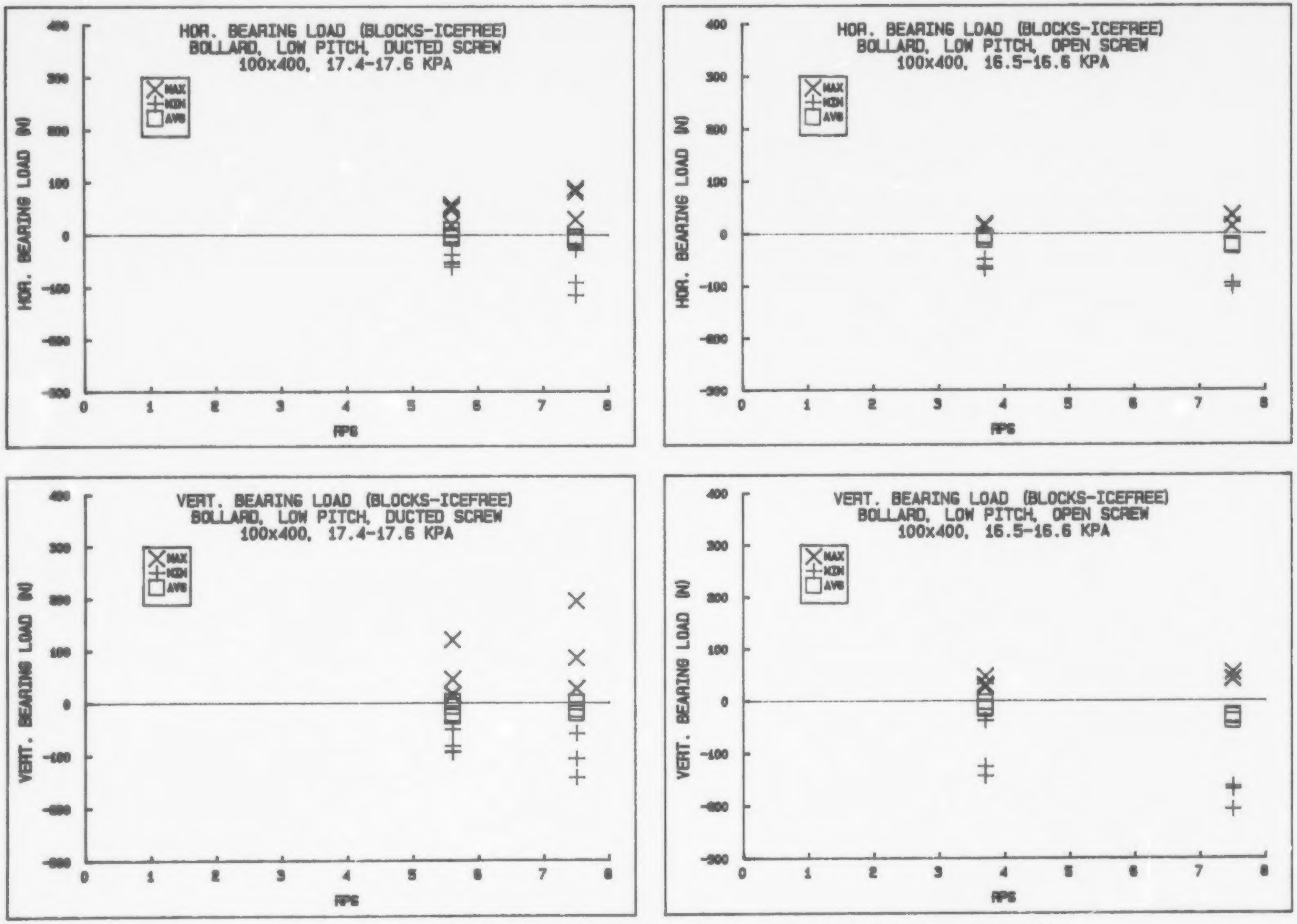


FIGURE 4.4.7 THE EFFECT OF RPS ON BEARING LOAD (HOR. AND VERT.) FOR LOW PITCH, LARGEST BLOCKS

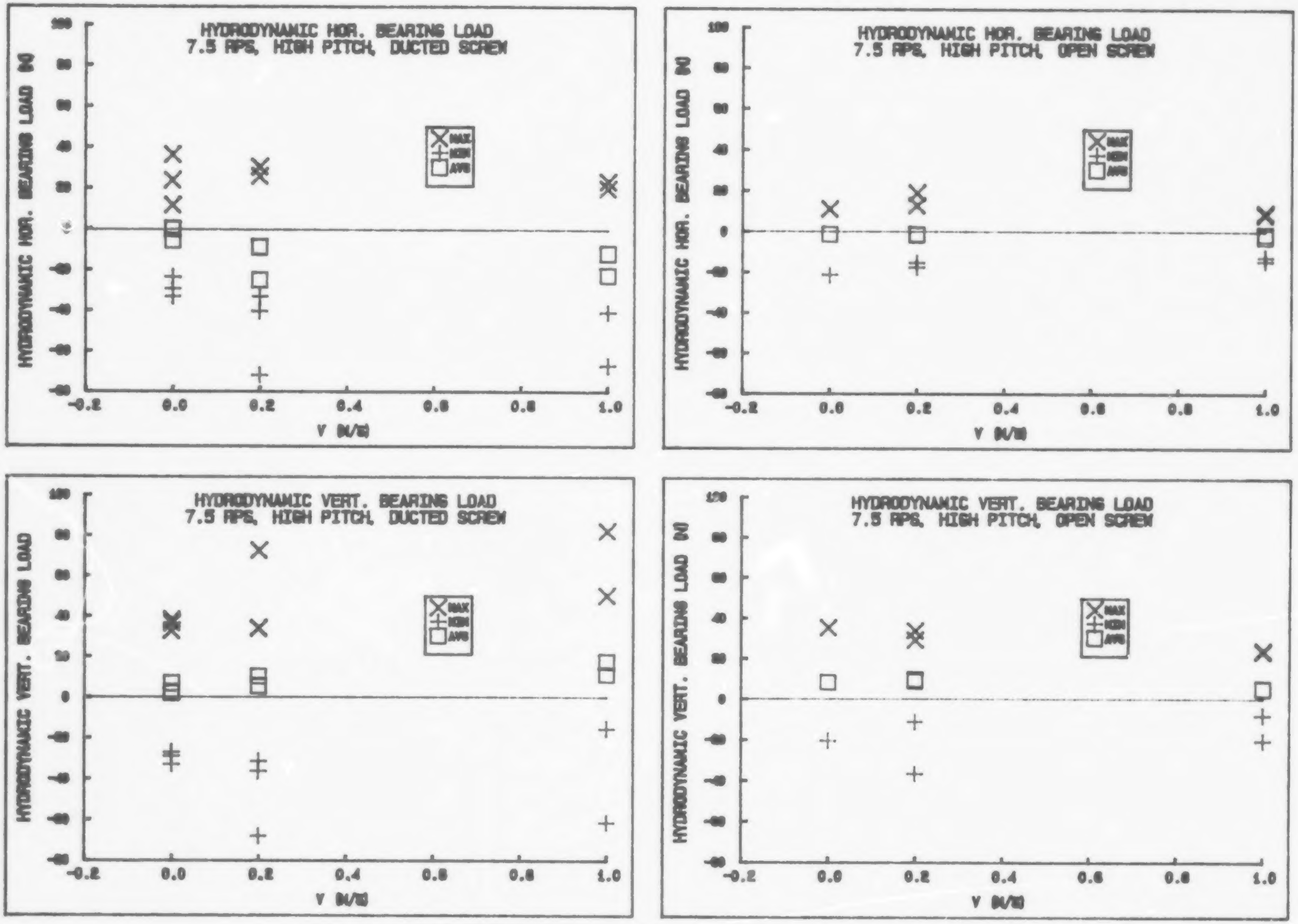


FIGURE 4.4.8 THE EFFECT OF VELOCITY ON HYDRODYNAMIC BEARING LOAD (HOR. AND VERT.), HIGH PITCH

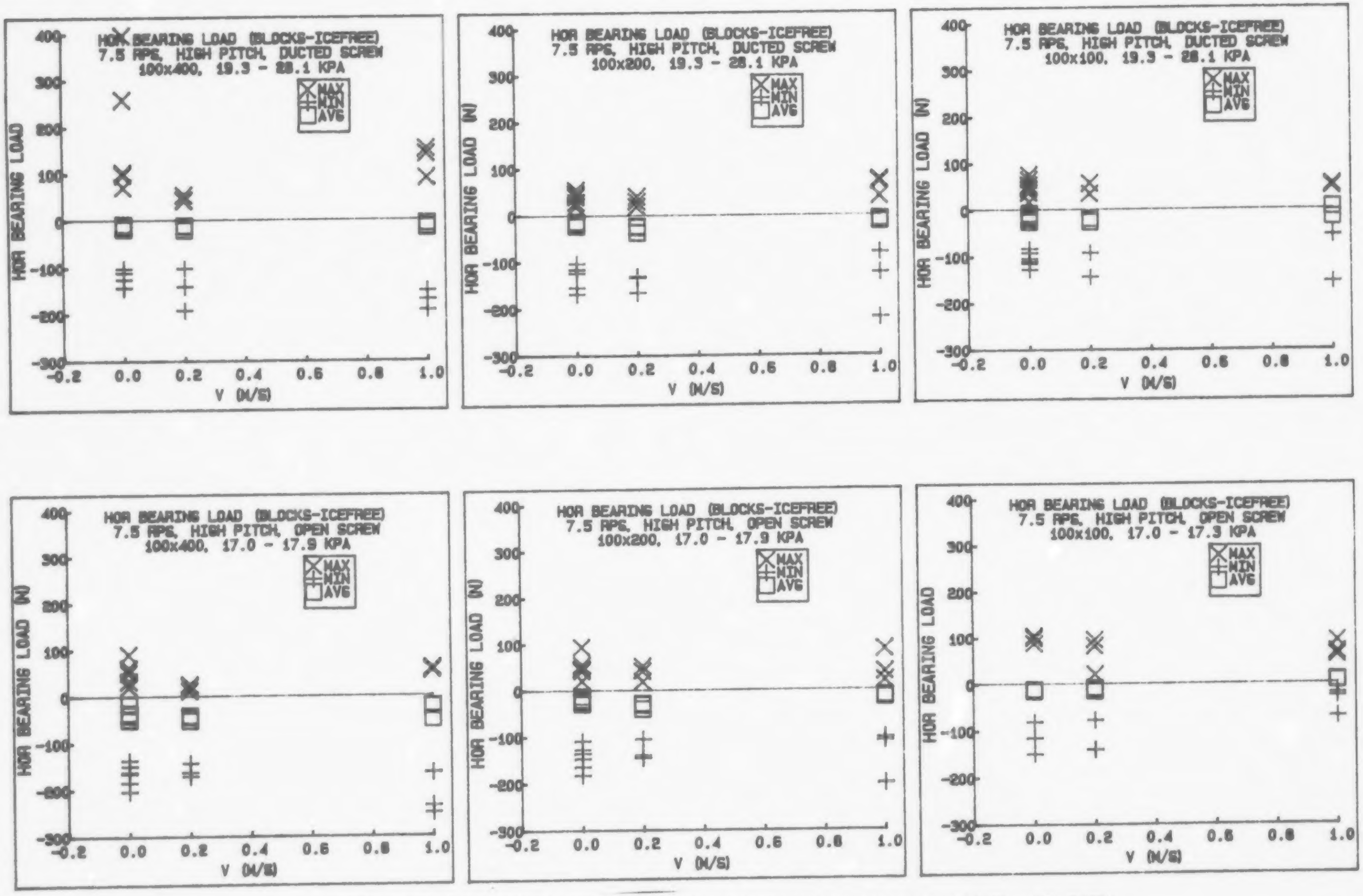


FIGURE 4.4.9 THE EFFECT OF VELOCITY ON HOR. BEARING LOAD FOR ALL BLOCK SIZES, HIGH PITCH

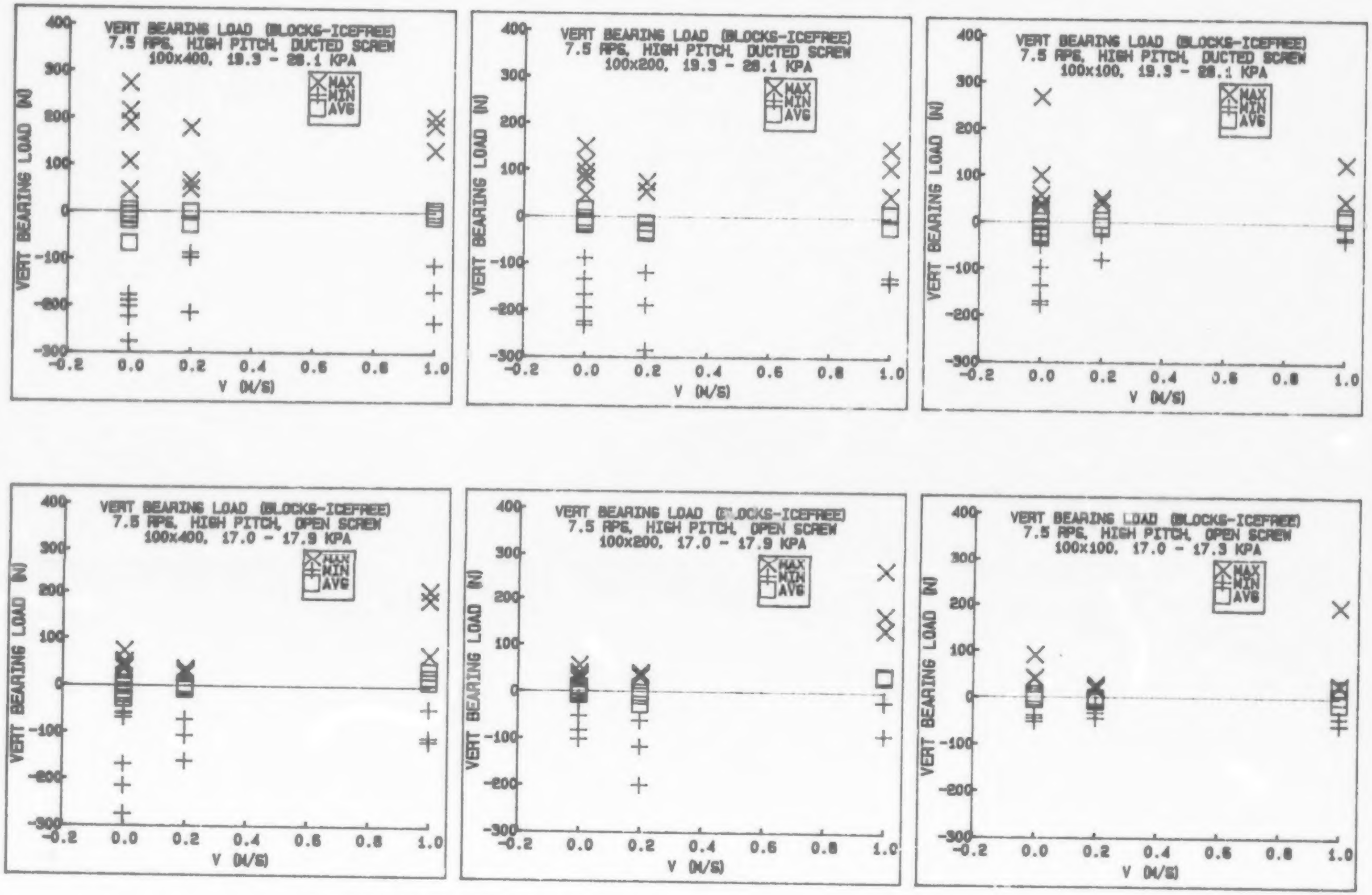


FIGURE 4.4.10 THE EFFECT OF VELOCITY ON VERT. BEARING LOAD FOR ALL BLOCK SIZES, HIGH PITCH

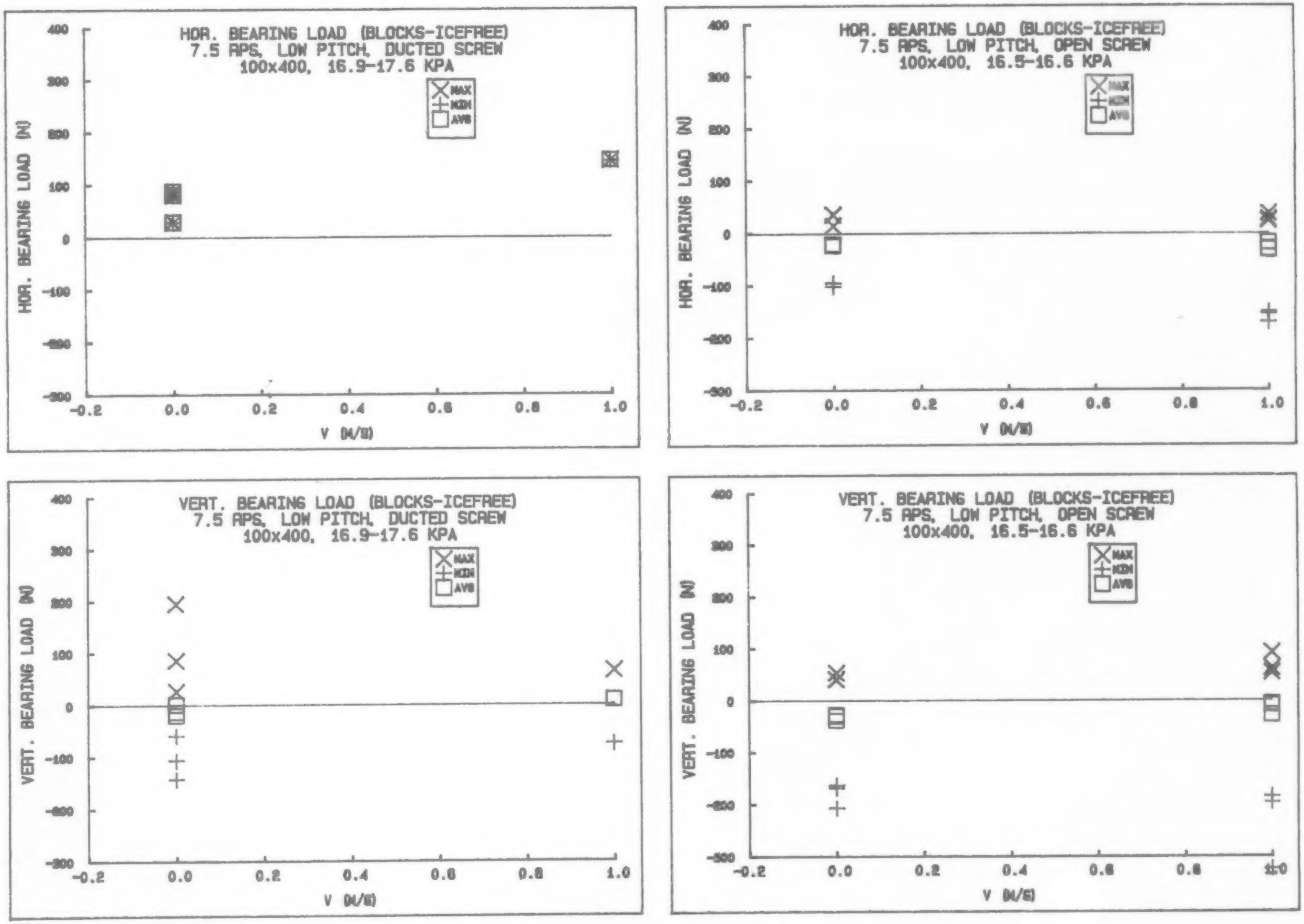


FIGURE 4.4.11 THE EFFECT OF VELOCITY ON BEARING LOAD (HOR. AND VERT.) FOR LOW PITCH, LARGEST BLOCKS

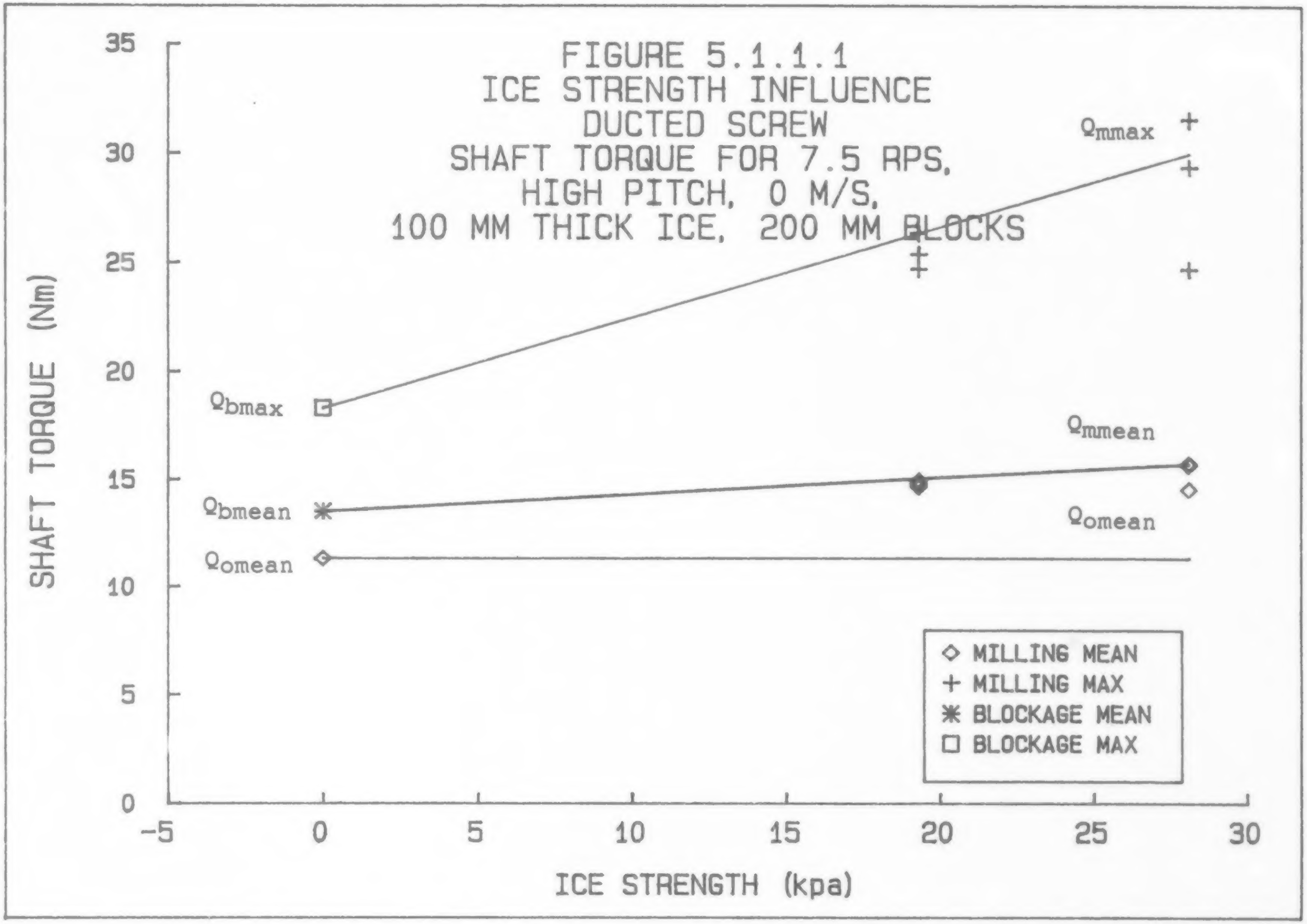


FIGURE 5.1.1.1
ICE STRENGTH INFLUENCE
DUCTED SCREW
SHAFT TORQUE FOR 7.5 RPS,
HIGH PITCH, 0 M/S,
100 MM THICK ICE, 200 MM BLOCKS

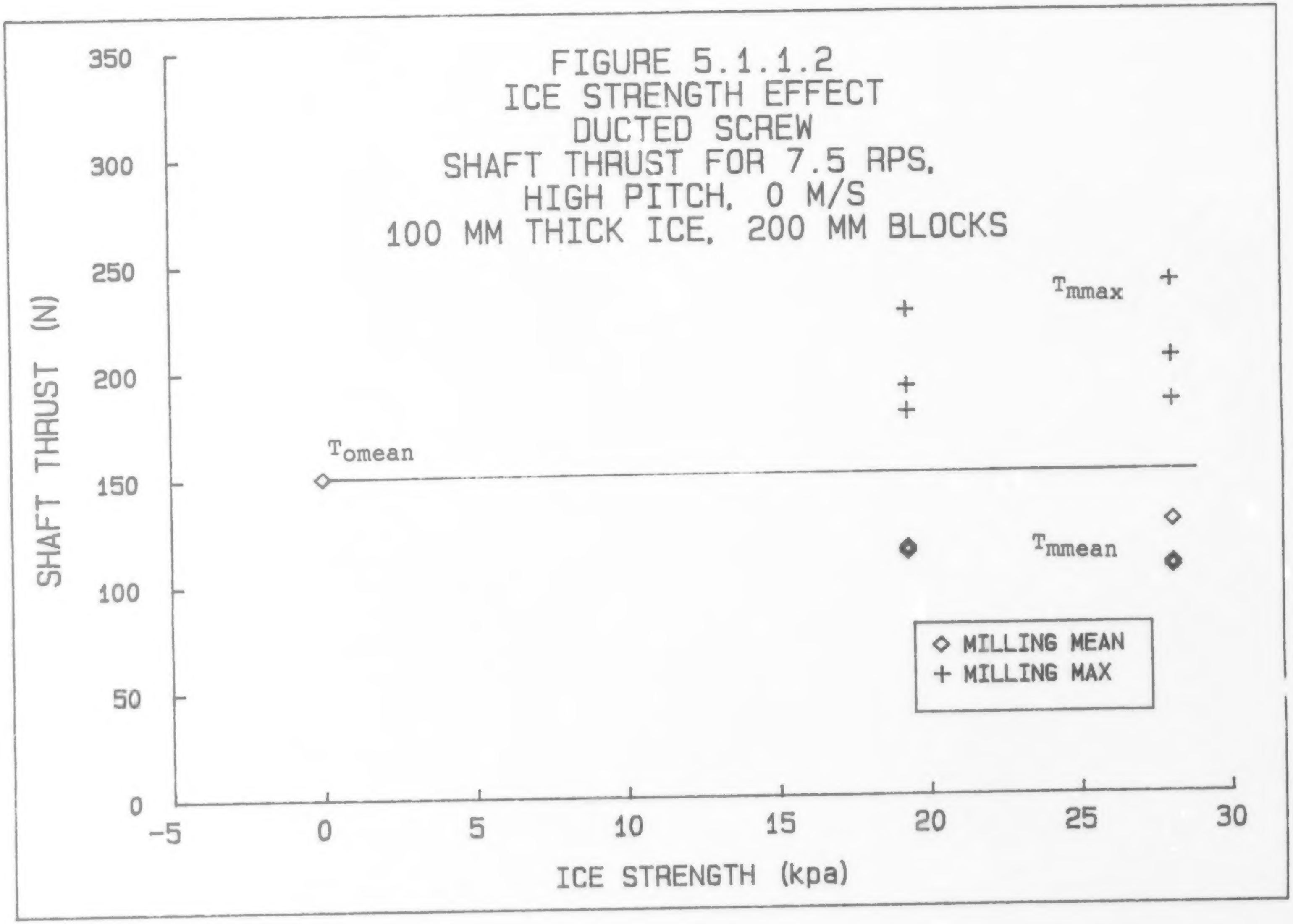


FIGURE 5.1.1.2
ICE STRENGTH EFFECT
DUCTED SCREW
SHAFT THRUST FOR 7.5 RPS,
HIGH PITCH, 0 M/S
100 MM THICK ICE, 200 MM BLOCKS

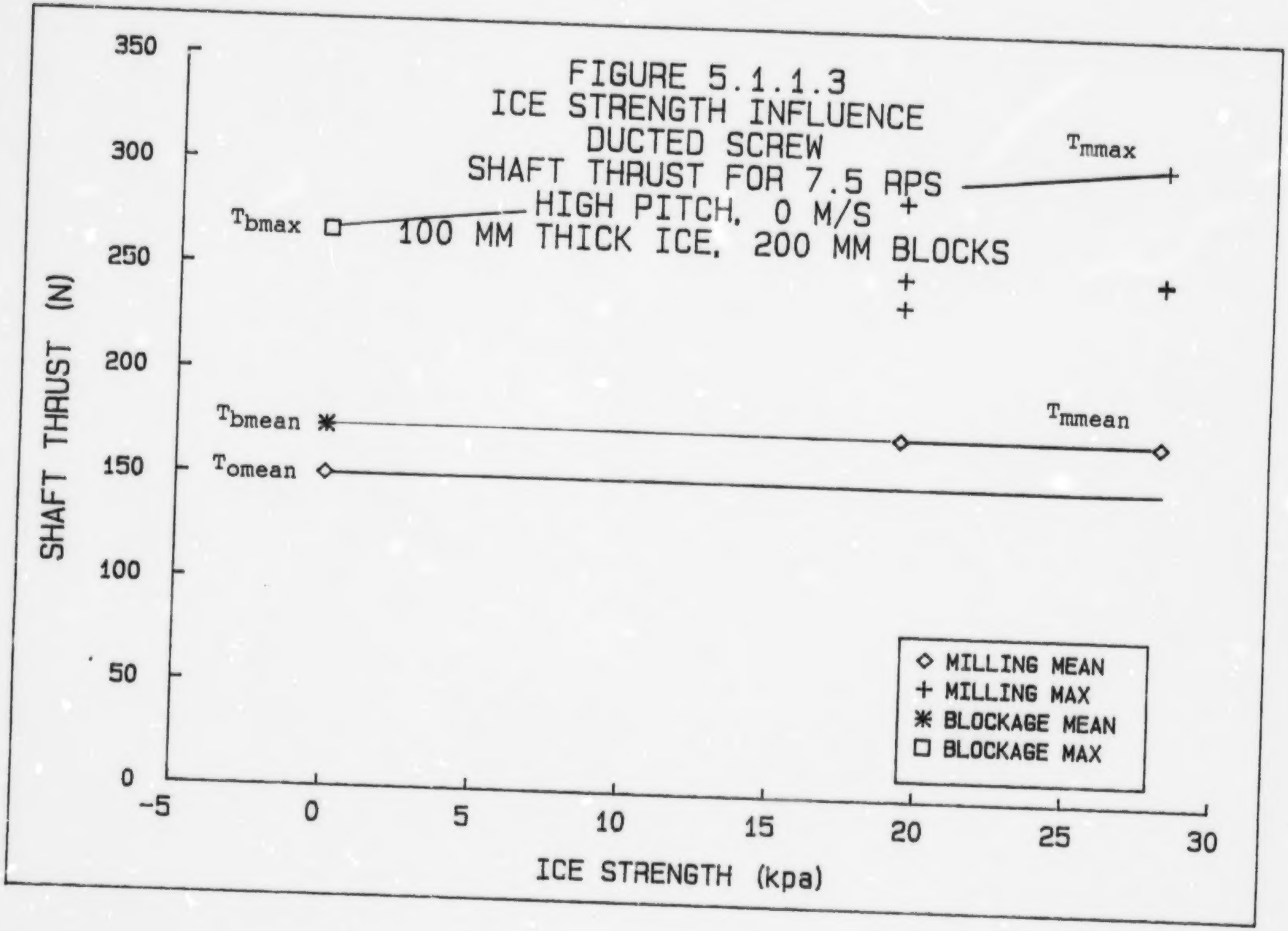


FIGURE 5.1.1.3
ICE STRENGTH INFLUENCE
DUCTED SCREW
SHAFT THRUST FOR 7.5 RPS
HIGH PITCH, 0 M/S
100 MM THICK ICE, 200 MM BLOCKS

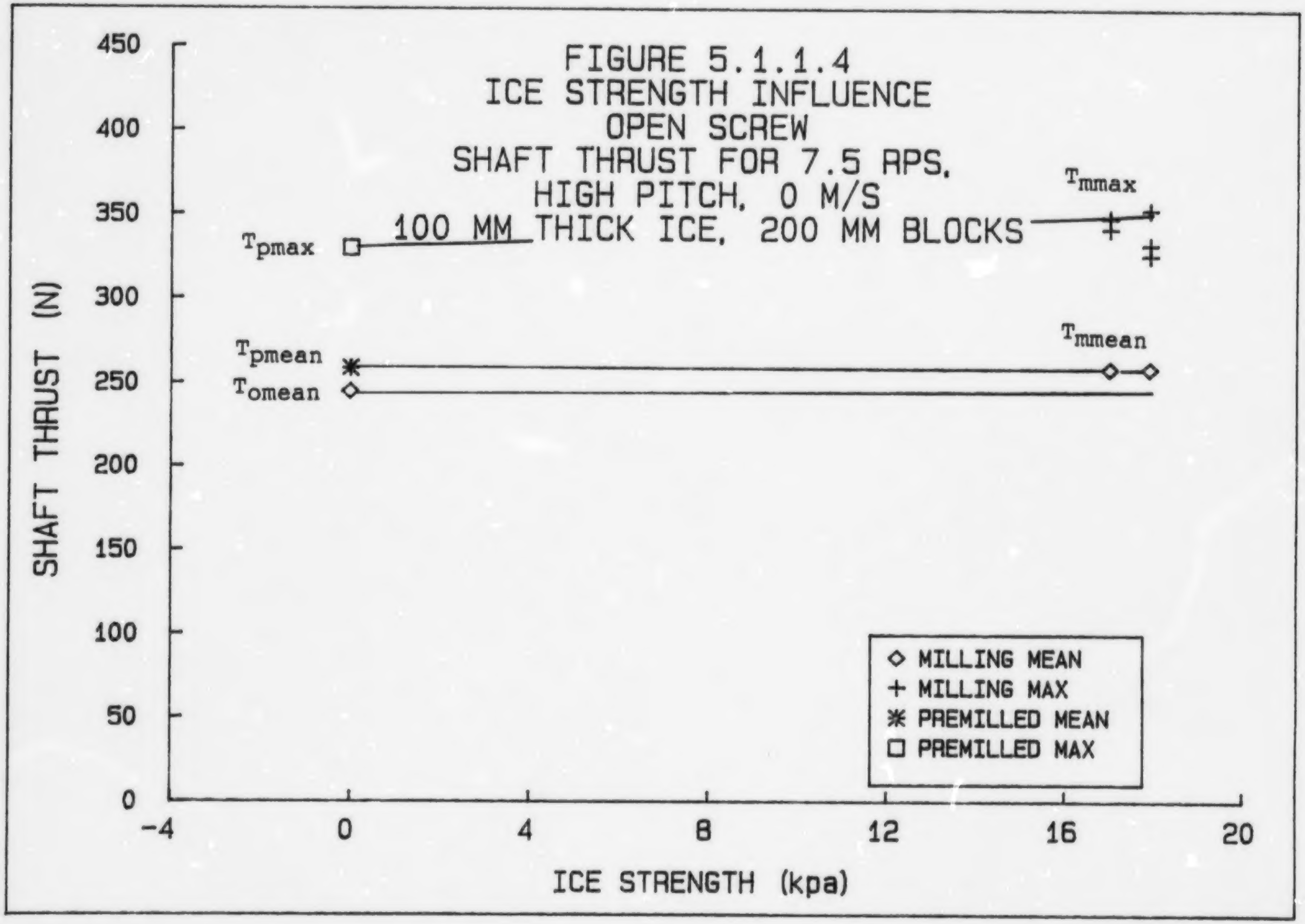


FIGURE 5.1.1.4
ICE STRENGTH INFLUENCE
OPEN SCREW
SHAFT THRUST FOR 7.5 RPS,
HIGH PITCH, 0 M/S
100 MM THICK ICE, 200 MM BLOCKS

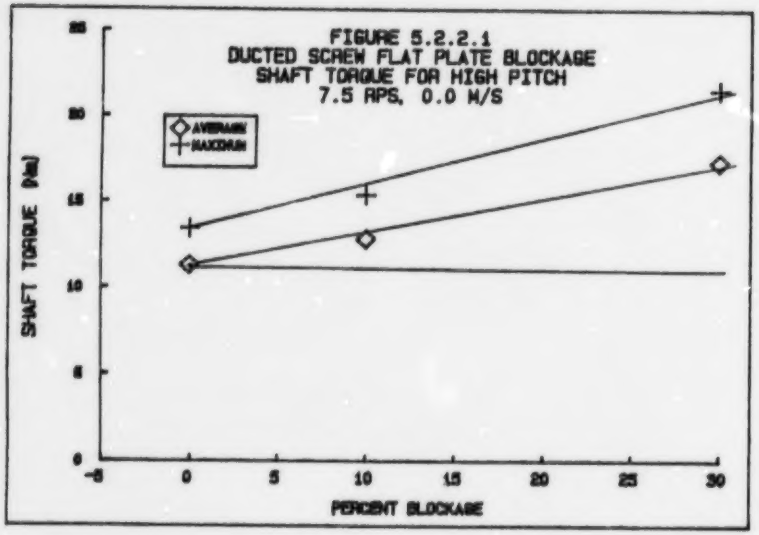


FIGURE 5.2.2.1
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT TORQUE FOR HIGH PITCH
7.5 RPS, 0.0 M/S

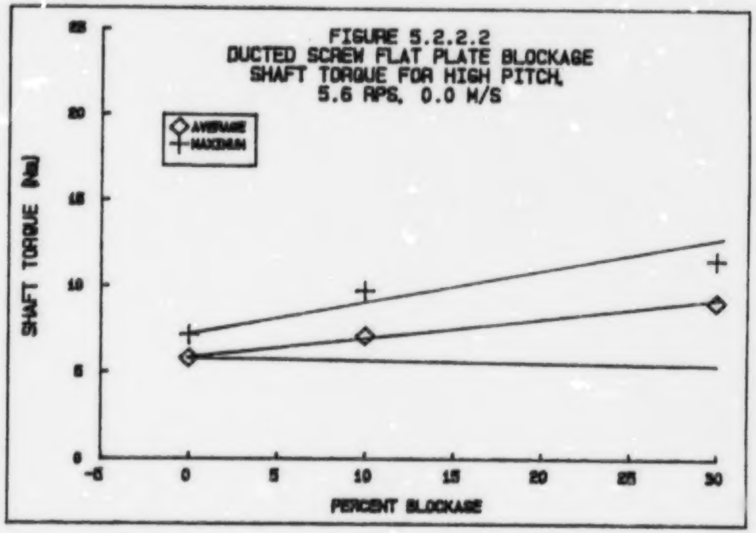


FIGURE 5.2.2.2
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT TORQUE FOR HIGH PITCH,
5.6 RPS, 0.0 M/S

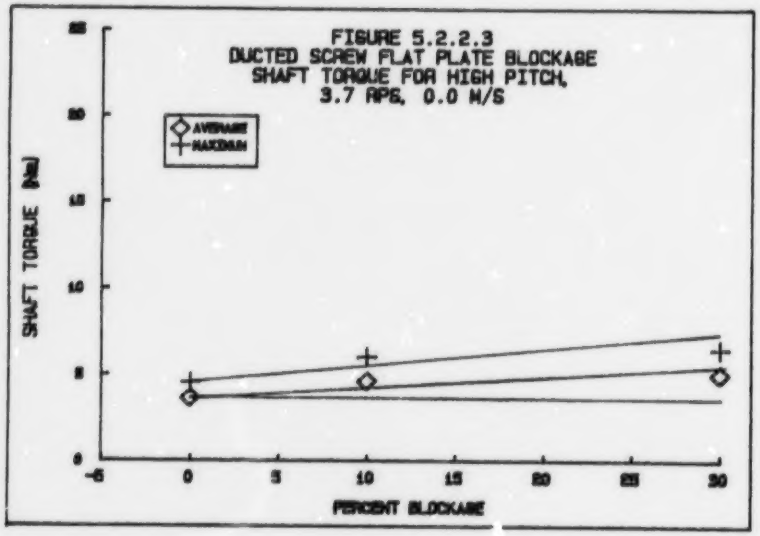


FIGURE 5.2.2.3
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT TORQUE FOR HIGH PITCH,
3.7 RPS, 0.0 M/S

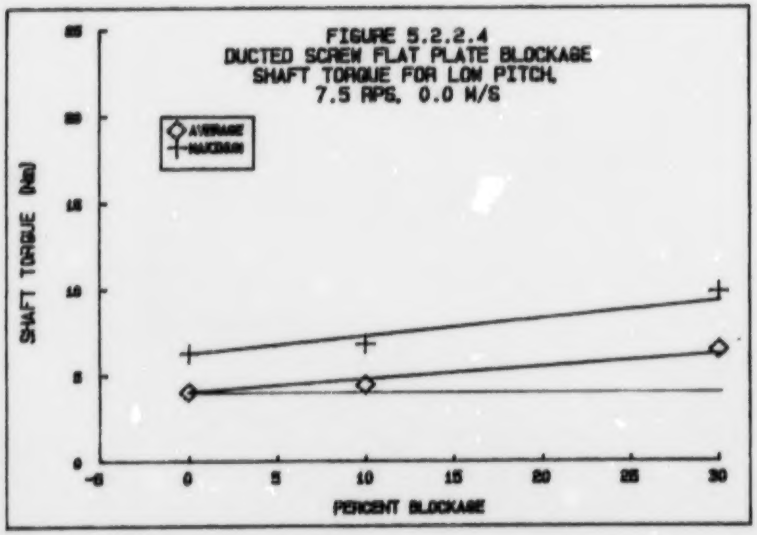


FIGURE 5.2.2.4
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT TORQUE FOR LOW PITCH,
7.5 RPS, 0.0 M/S

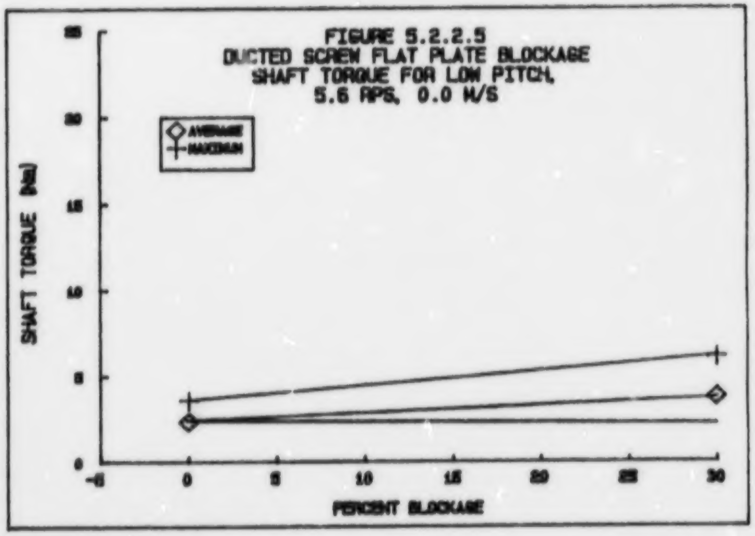


FIGURE 5.2.2.5
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT TORQUE FOR LOW PITCH,
5.6 RPS, 0.0 M/S

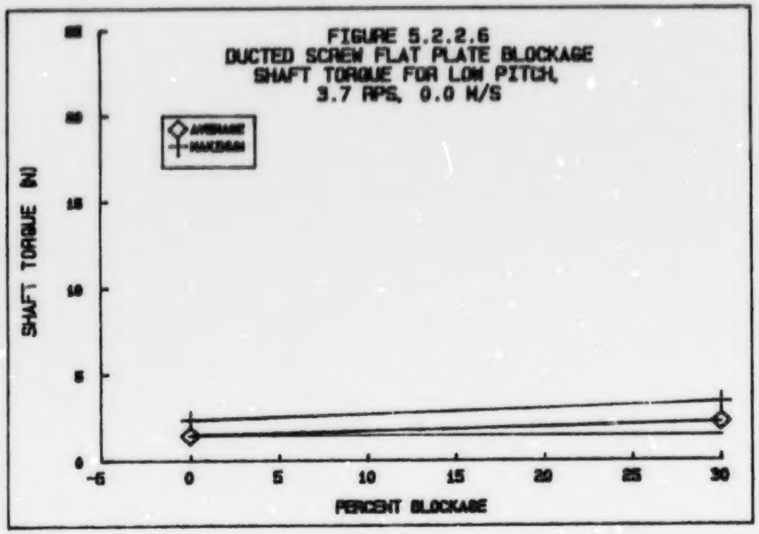
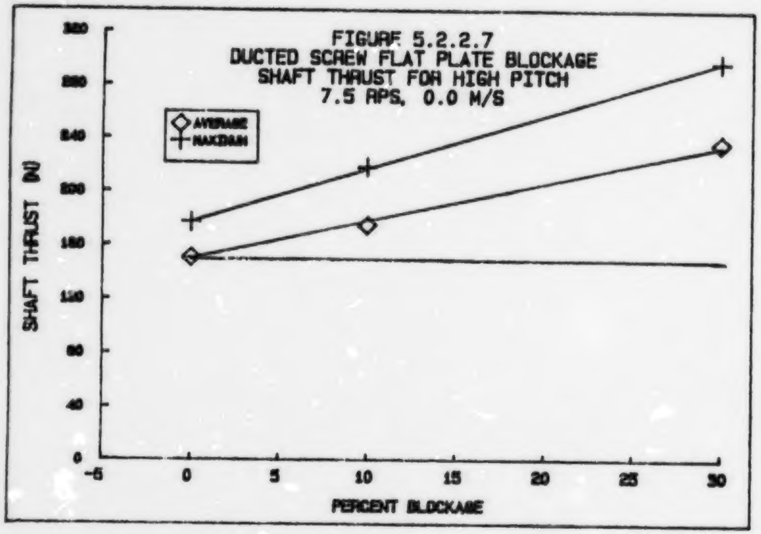


FIGURE 5.2.2.6
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT TORQUE FOR LOW PITCH,
3.7 RPS, 0.0 M/S



FIGURF 5.2.2.7
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT THRUST FOR HIGH PITCH
7.5 RPS, 0.0 M/S

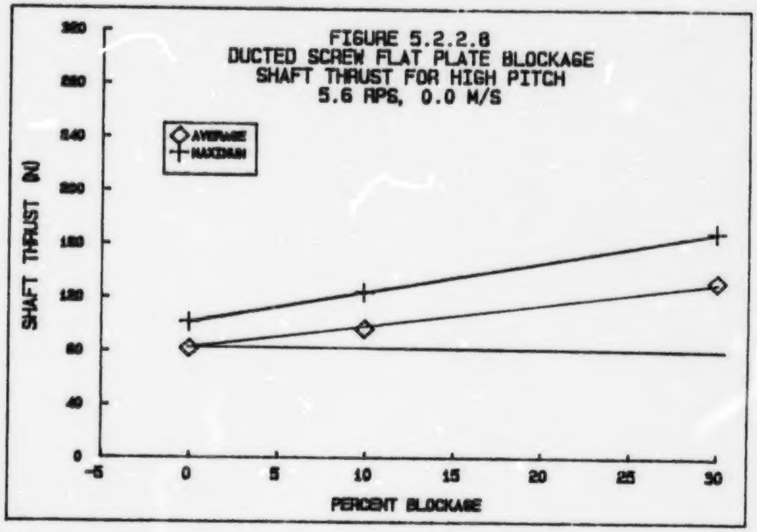


FIGURE 5.2.2.8
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT THRUST FOR HIGH PITCH
5.6 RPS, 0.0 M/S

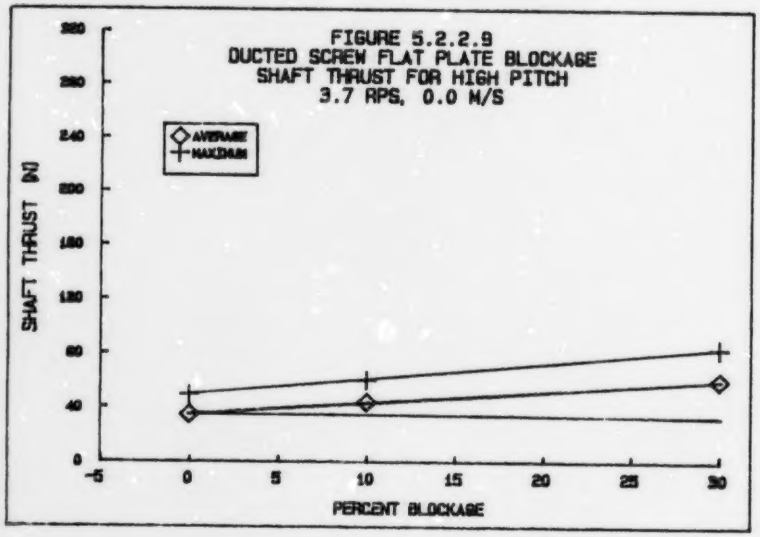


FIGURE 5.2.2.9
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT THRUST FOR HIGH PITCH
3.7 RPS, 0.0 M/S

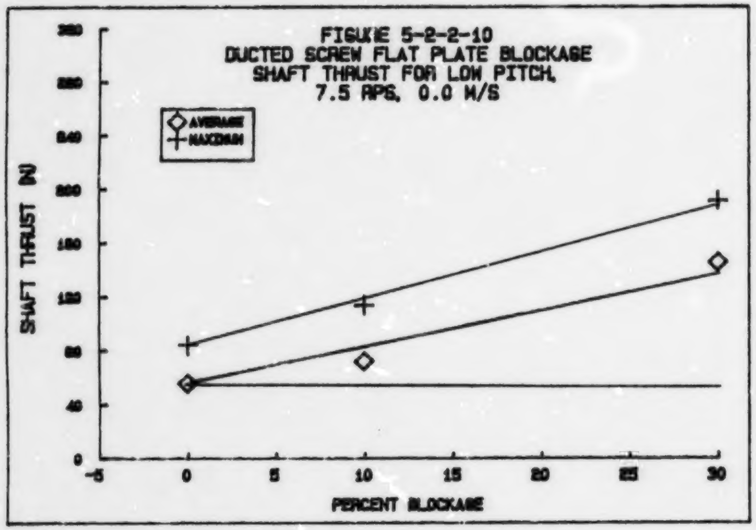


FIGURE 5-2-2-10
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT THRUST FOR LOW PITCH,
7.5 RPS, 0.0 M/S

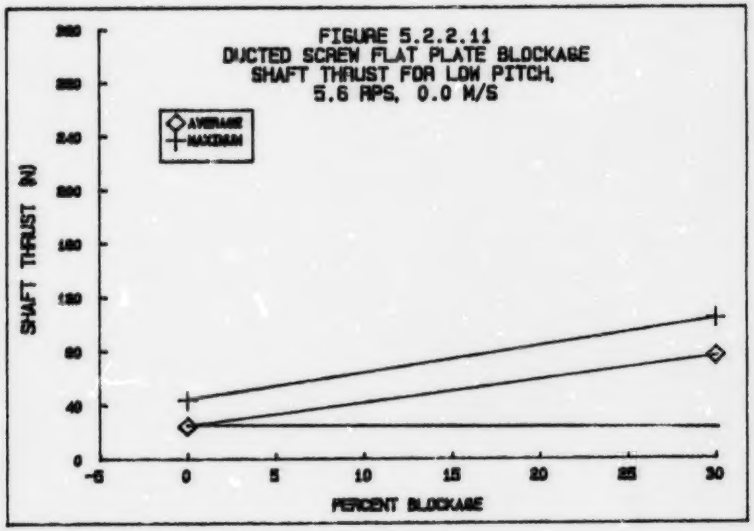


FIGURE 5.2.2.11
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT THRUST FOR LOW PITCH,
5.6 RPS, 0.0 M/S

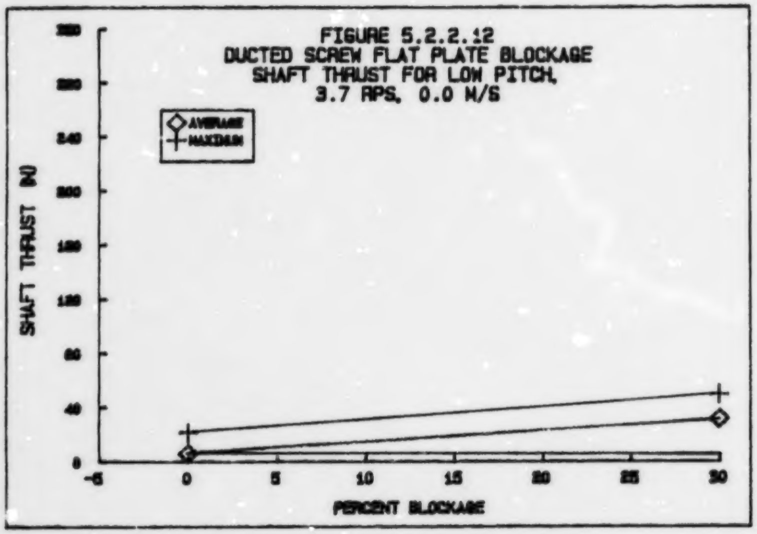


FIGURE 5.2.2.12
DUCTED SCREW FLAT PLATE BLOCKAGE
SHAFT THRUST FOR LOW PITCH,
3.7 RPS, 0.0 M/S

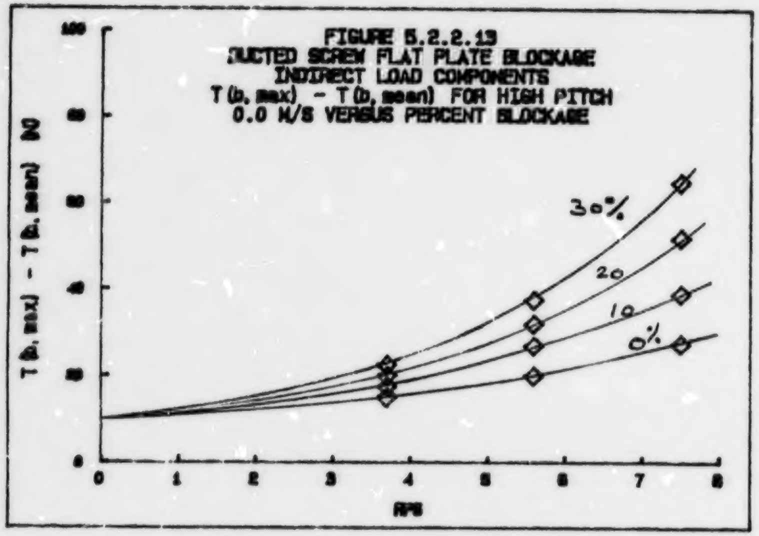


FIGURE 5.2.2.13
DUCTED SCREW FLAT PLATE BLOCKAGE
INDIRECT LOAD COMPONENTS
T (b, max) - T (b, mean) FOR HIGH PITCH
0.0 M/S VERSUS PERCENT BLOCKAGE

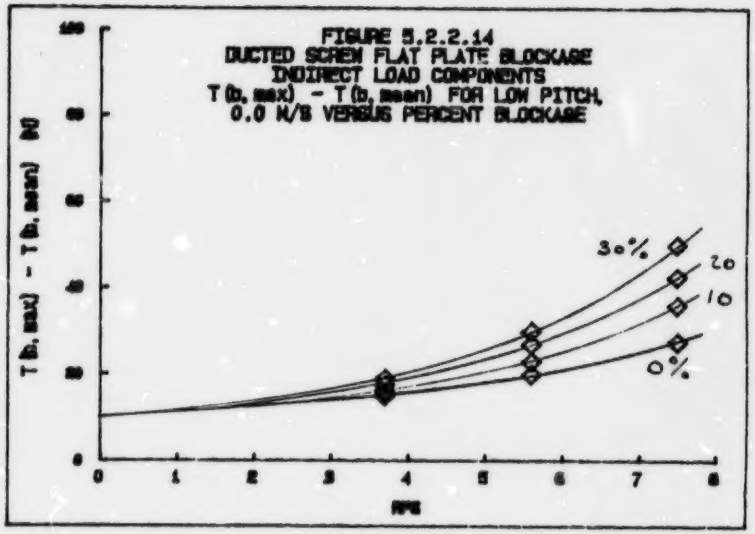


FIGURE 5.2.2.14
DUCTED SCREW FLAT PLATE BLOCKAGE
INDIRECT LOAD COMPONENTS
T (b, max) - T (b, mean) FOR LOW PITCH,
0.0 M/S VERSUS PERCENT BLOCKAGE

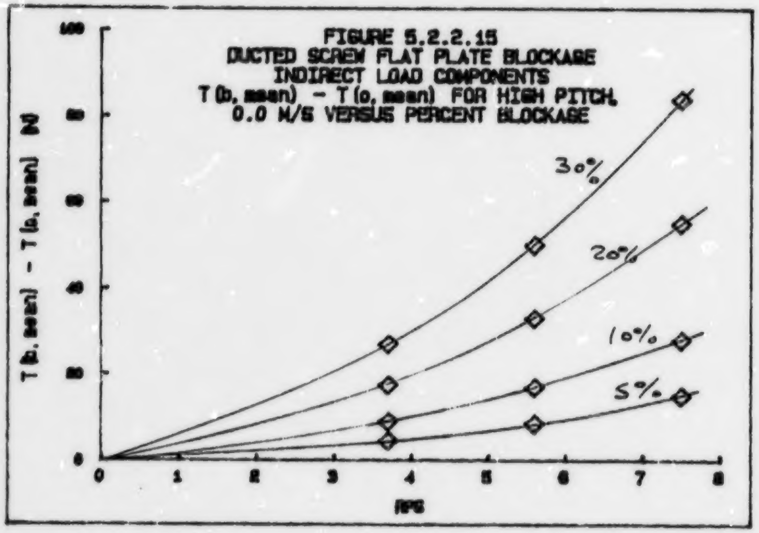


FIGURE 5.2.2.15
DUCTED SCREW FLAT PLATE BLOCKAGE
INDIRECT LOAD COMPONENTS
T (b, mean) - T (o, mean) FOR HIGH PITCH,
0.0 M/S VERSUS PERCENT BLOCKAGE

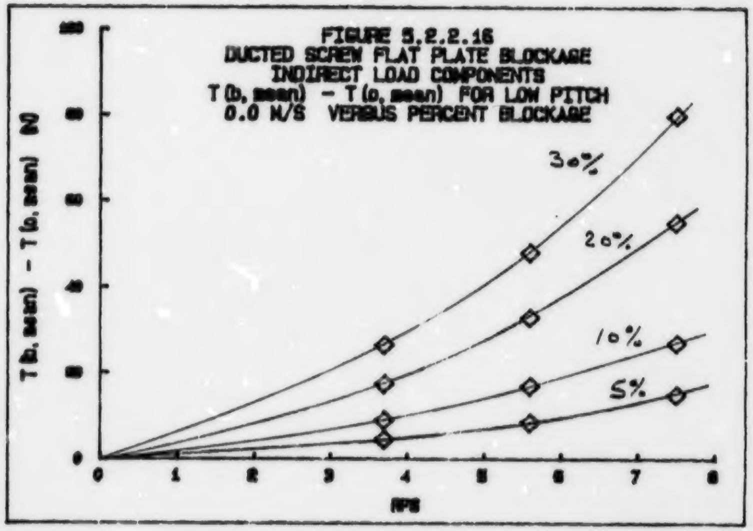


FIGURE 5.2.2.16
DUCTED SCREW FLAT PLATE BLOCKAGE
INDIRECT LOAD COMPONENTS
T (b, mean) - T (o, mean) FOR LOW PITCH
0.0 M/S VERSUS PERCENT BLOCKAGE

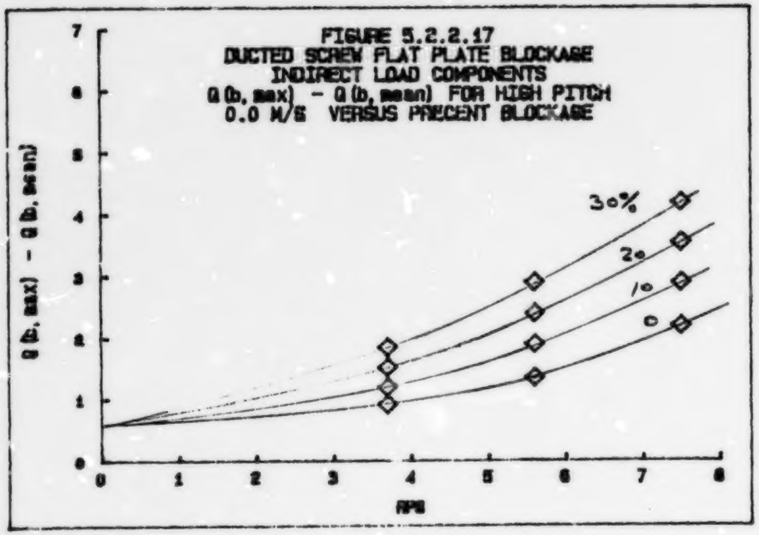


FIGURE 5.2.2.17
DUCTED SCREW FLAT PLATE BLOCKAGE
INDIRECT LOAD COMPONENTS
Q (b, max) - Q (b, mean) FOR HIGH PITCH
0.0 M/S VERSUS PRECENT BLOCKAGE

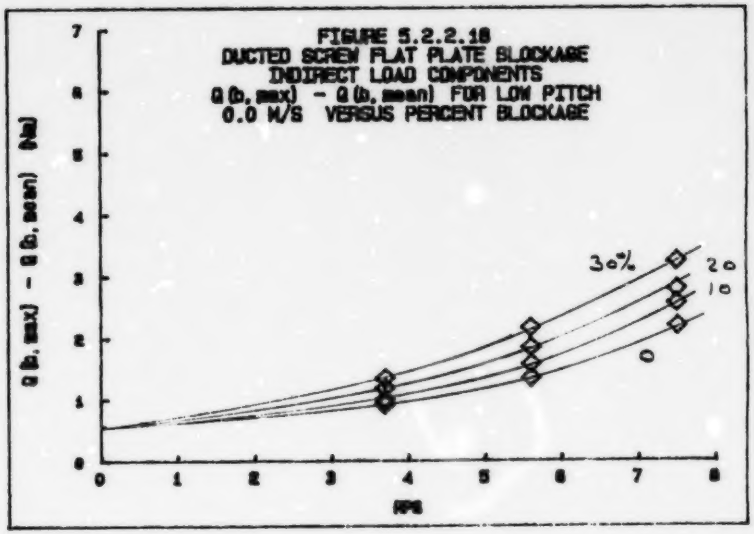


FIGURE 5.2.2.18
DUCTED SCREW FLAT PLATE BLOCKAGE
INDIRECT LOAD COMPONENTS
Q (b, max) - Q (b, mean) FOR LOW PITCH
0.0 M/S VERSUS PERCENT BLOCKAGE

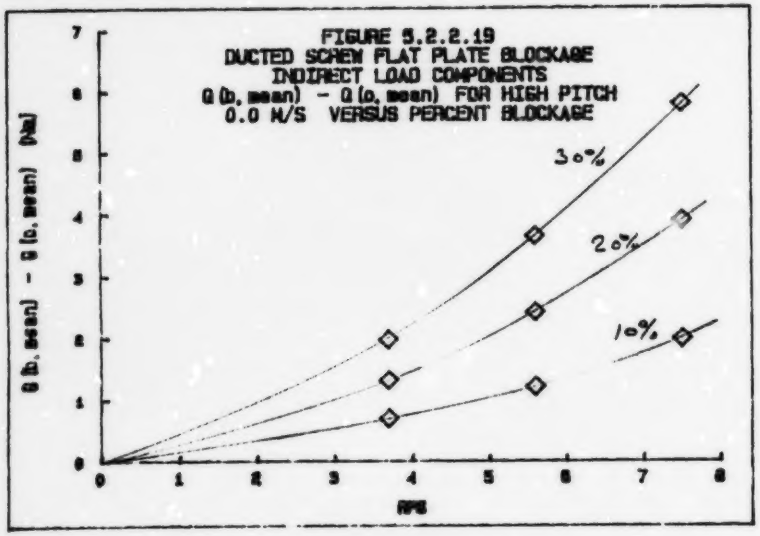


FIGURE 5.2.2.19
DUCTED SCREW FLAT PLATE BLOCKAGE
INDIRECT LOAD COMPONENTS
Q (b, mean) - Q (o, mean) FOR HIGH PITCH
0.0 M/S VERSUS PERCENT BLOCKAGE

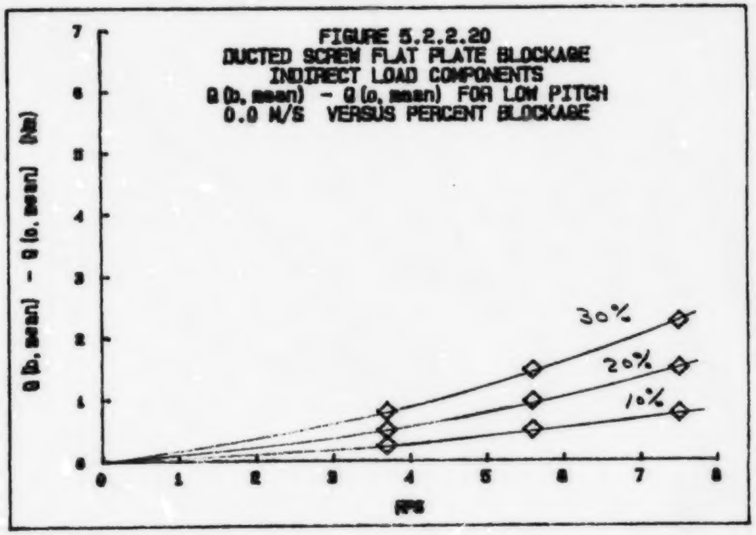
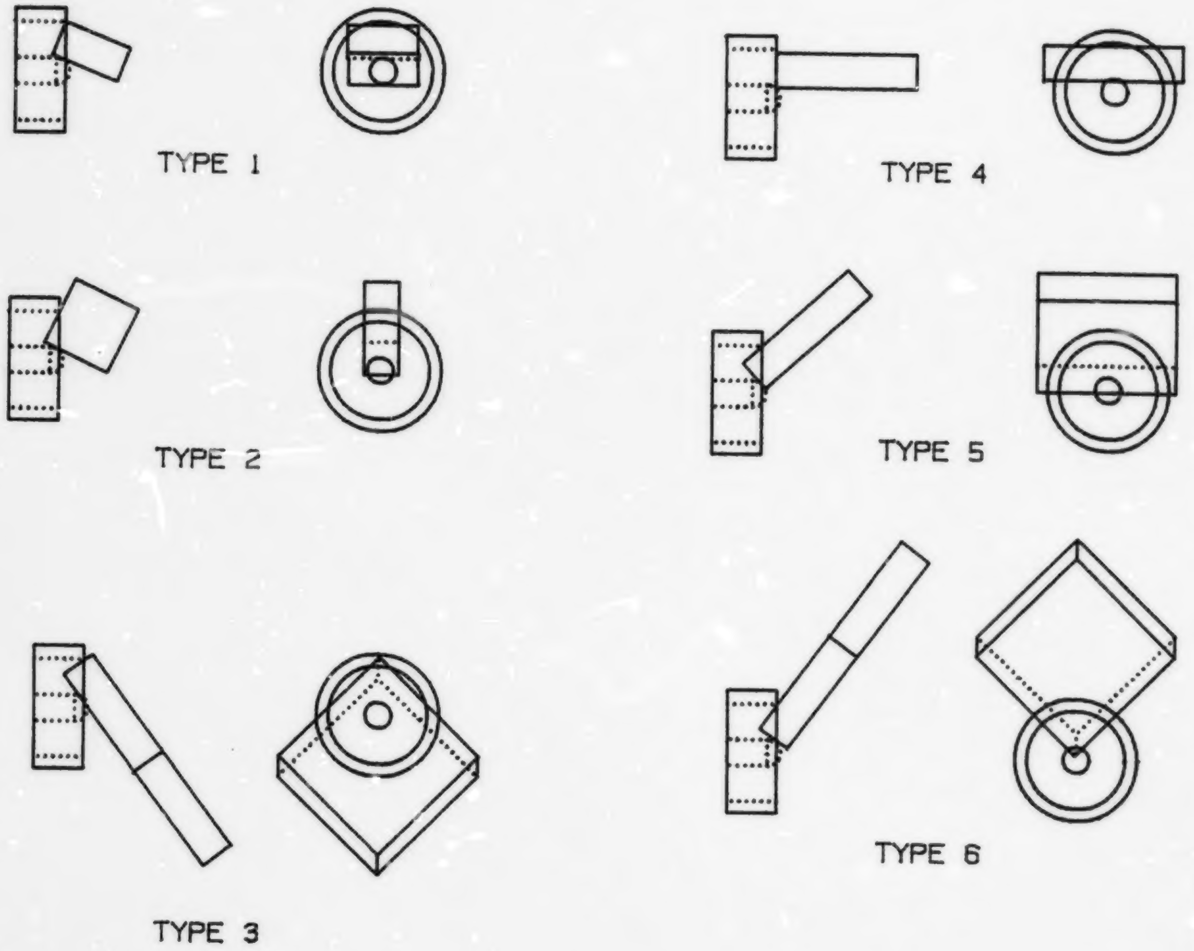


FIGURE 5.2.2.20
DUCTED SCREW FLAT PLATE BLOCKAGE
INDIRECT LOAD COMPONENTS
Q (b, mean) - Q (o, mean) FOR LOW PITCH
0.0 M/S VERSUS PERCENT BLOCKAGE

FIGURE 5.2.2.21

ICE BLOCK BLOCKAGE TYPES



TYPE 1

TYPE 2

TYPE 3

TYPE 4

TYPE 5

TYPE 6

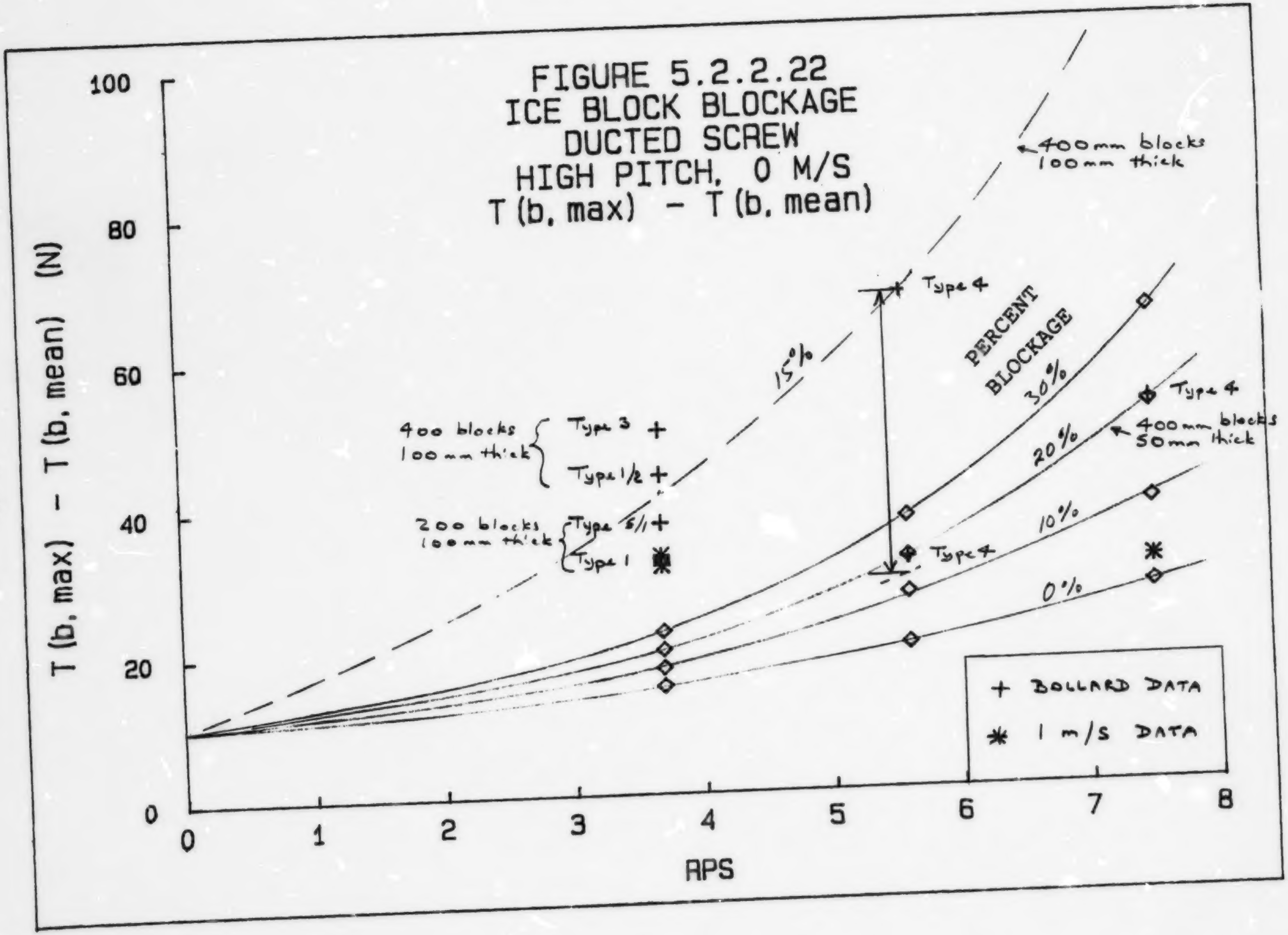


FIGURE 5.2.2.22
ICE BLOCK BLOCKAGE
DUCTED SCREW
HIGH PITCH, 0 M/S
T (b, max) - T (b, mean)

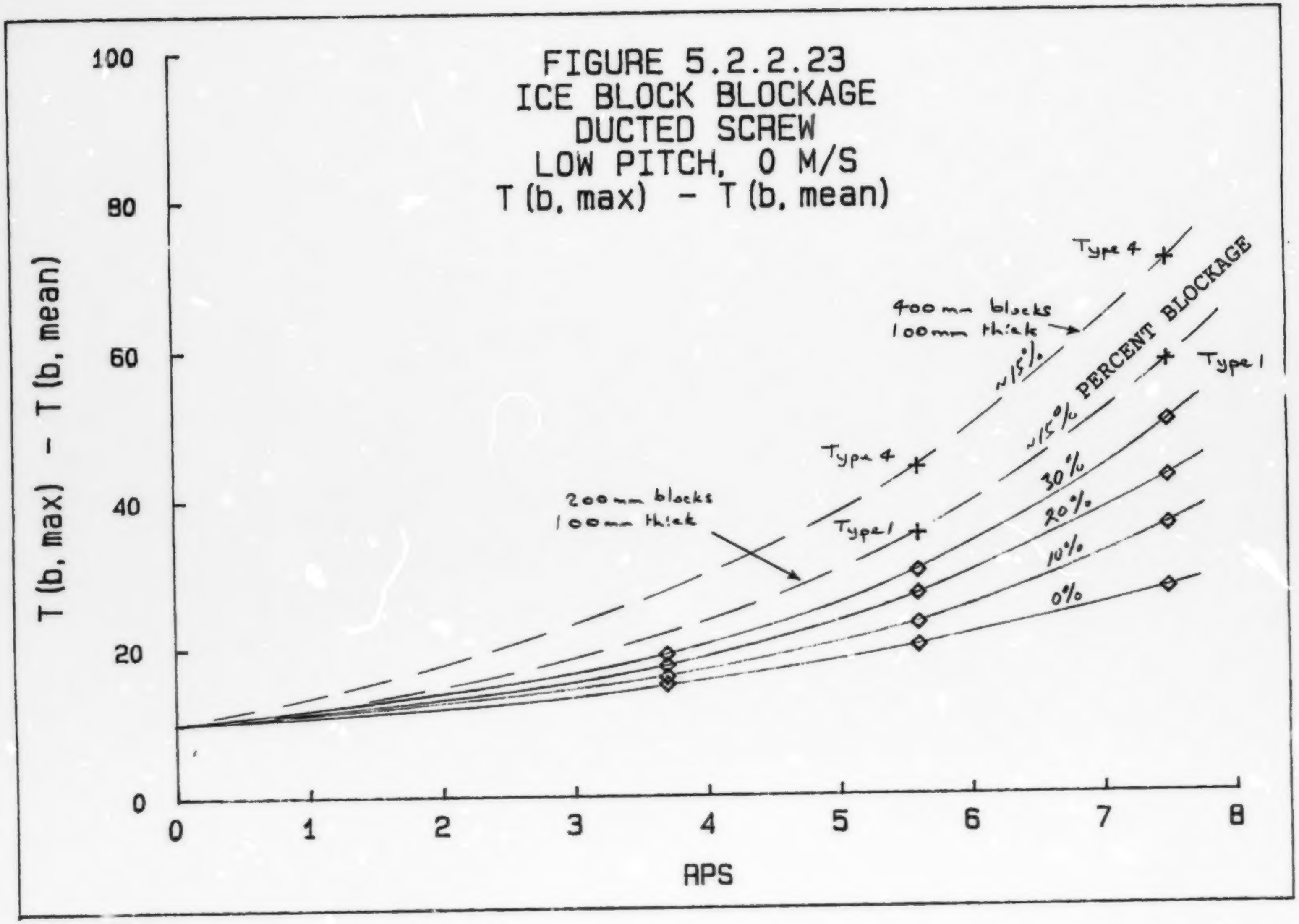


FIGURE 5.2.2.23
ICE BLOCK BLOCKAGE
DUCTED SCREW
LOW PITCH, 0 M/S
T (b, max) - T (b, mean)

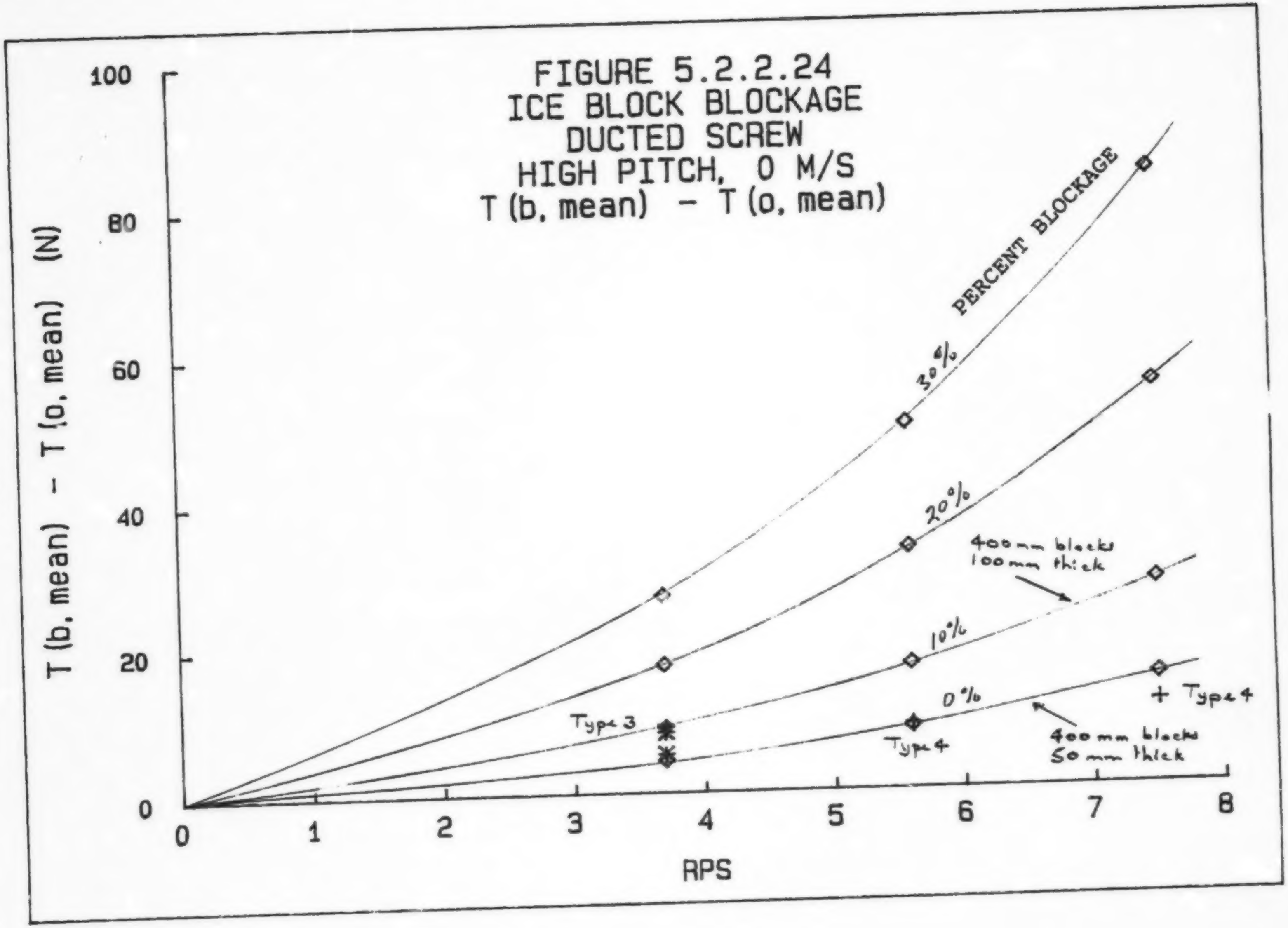


FIGURE 5.2.2.24
ICE BLOCK BLOCKAGE
DUCTED SCREW
HIGH PITCH, 0 M/S
T (b, mean) - T (o, mean)

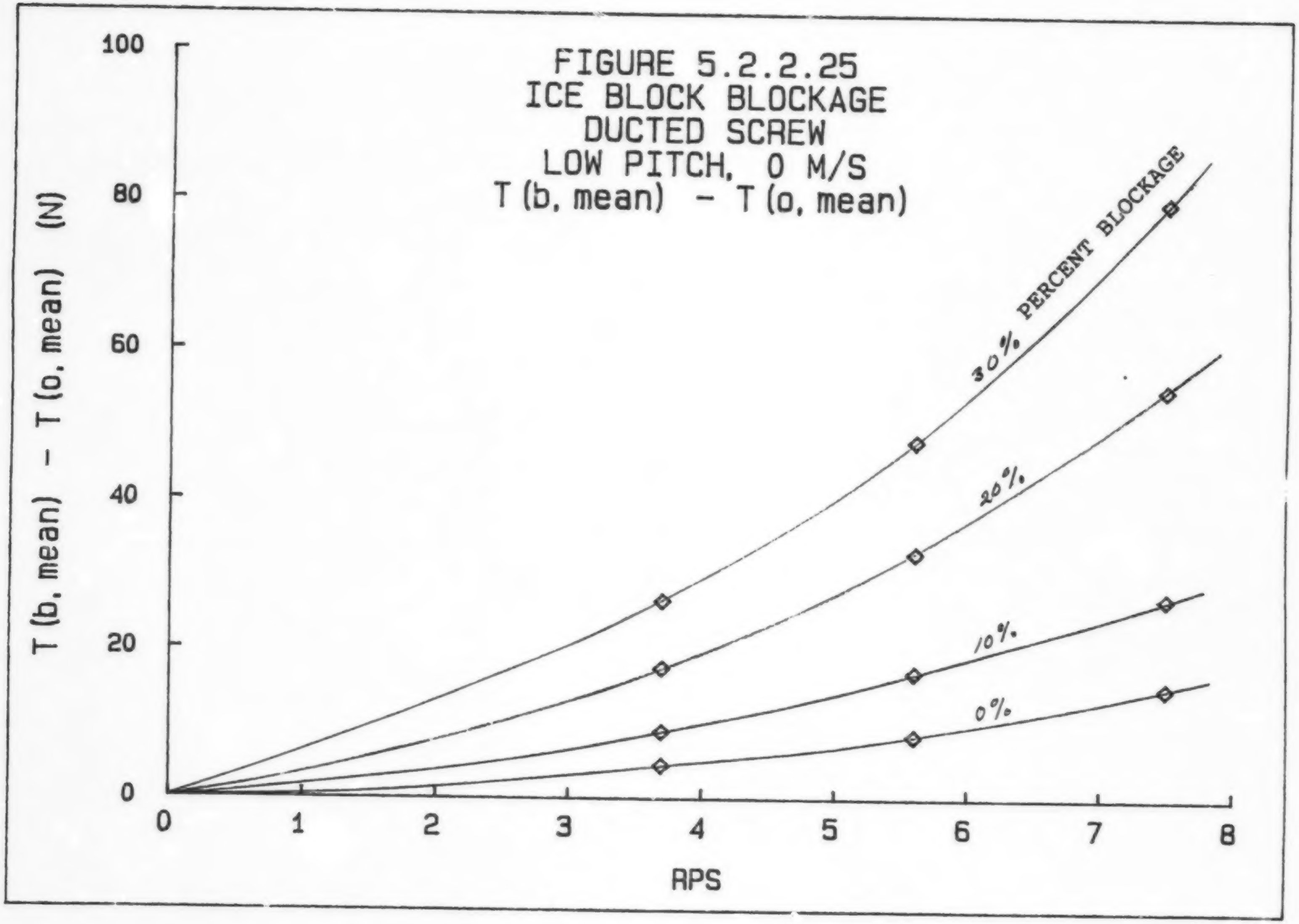


FIGURE 5.2.2.25
ICE BLOCK BLOCKAGE
DUCTED SCREW
LOW PITCH, 0 M/S
T (b, mean) - T (o, mean)

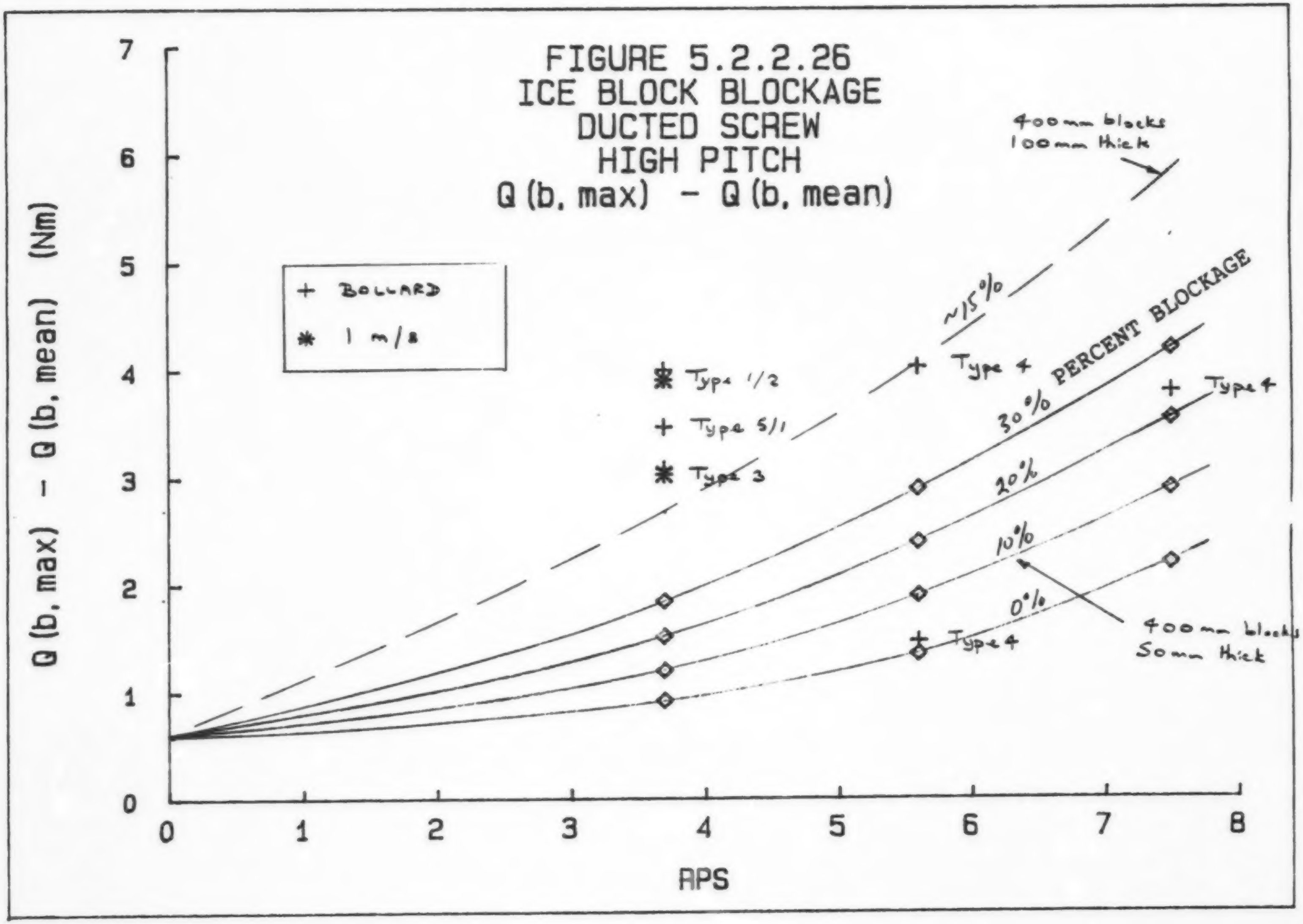


FIGURE 5.2.2.26
ICE BLOCK BLOCKAGE
DUCTED SCREW
HIGH PITCH
Q (b, max) - Q (b, mean)

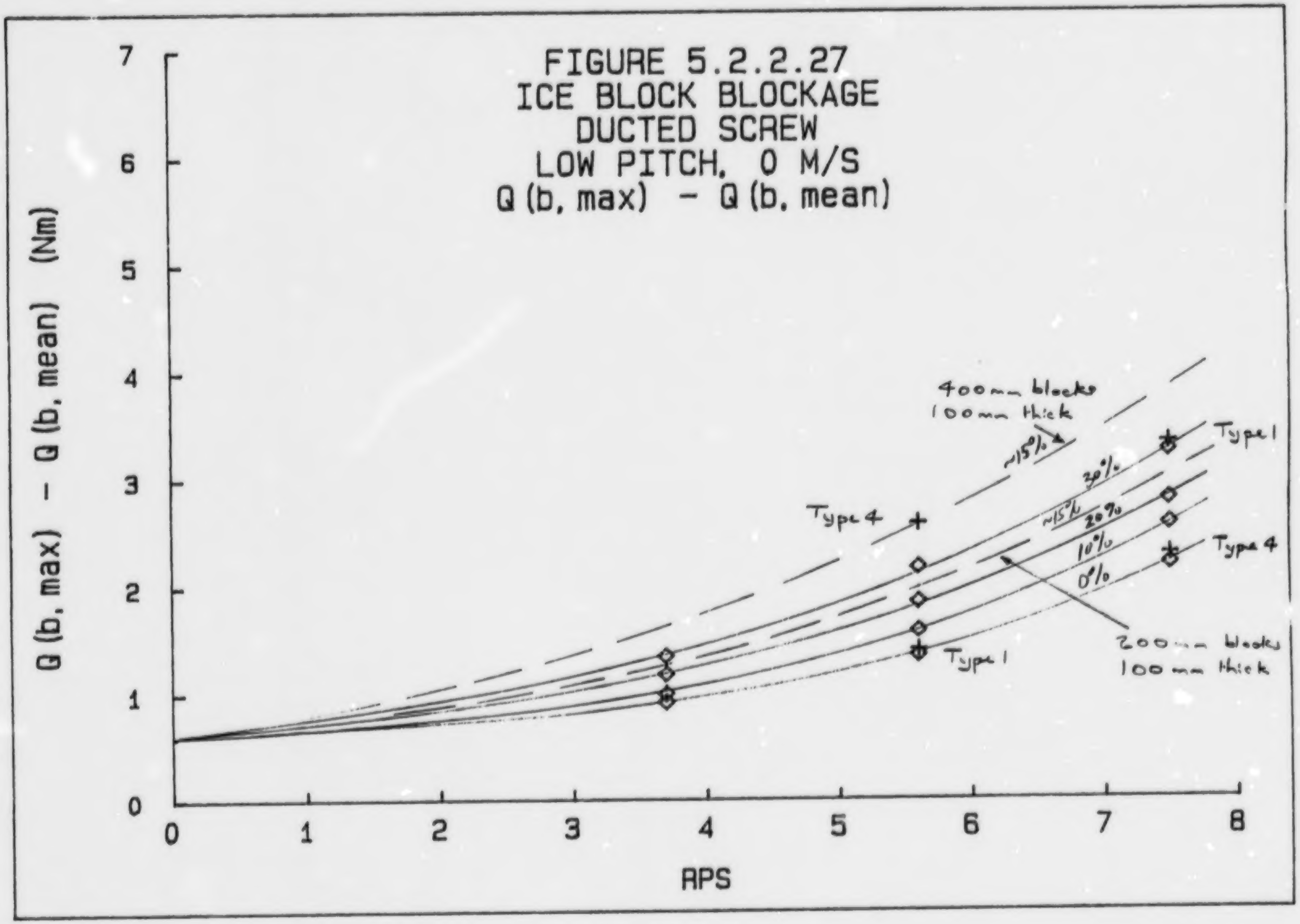


FIGURE 5.2.2.27
ICE BLOCK BLOCKAGE
DUCTED SCREW
LOW PITCH, 0 M/S
Q (b, max) − Q (b, mean)

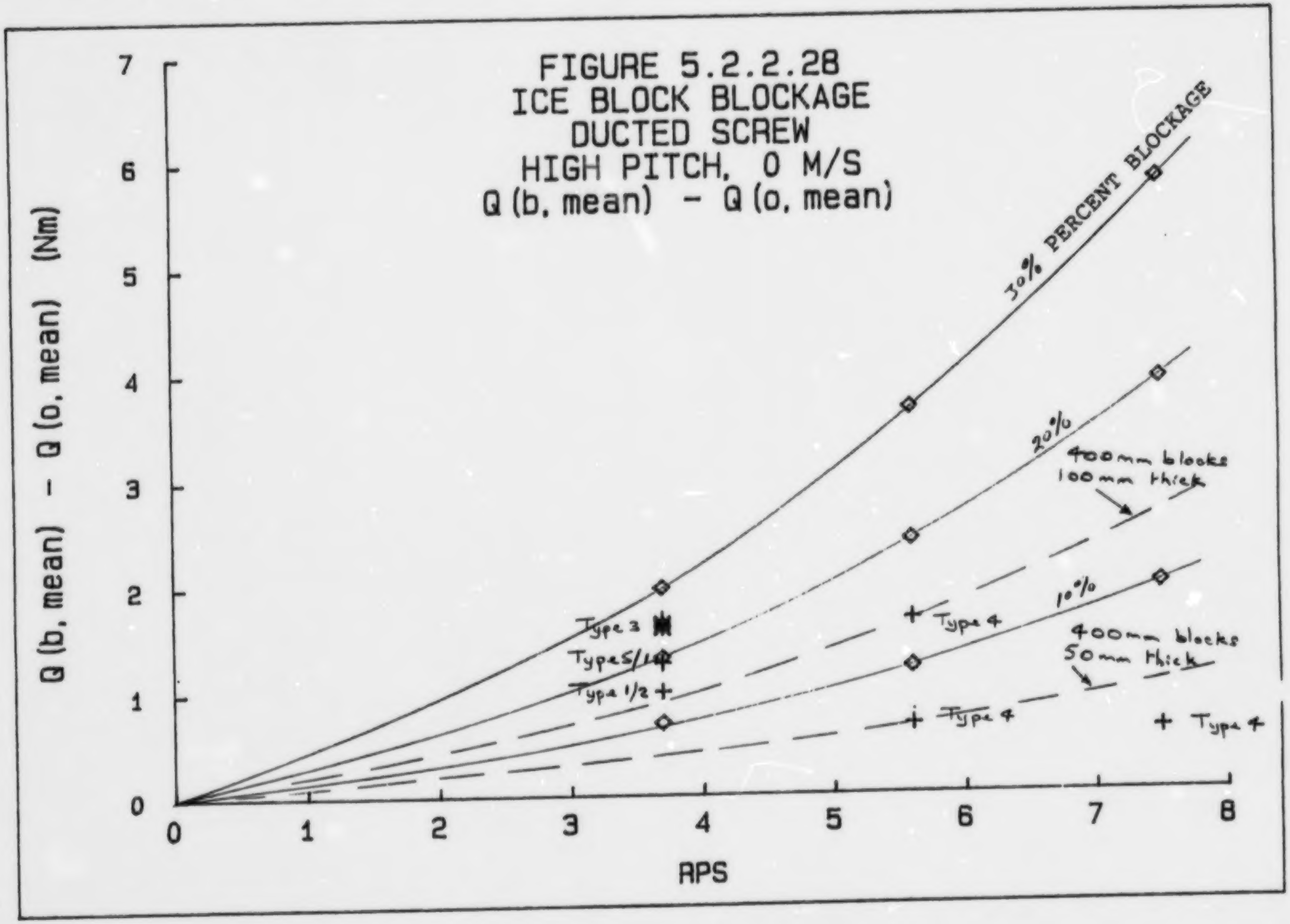


FIGURE 5.2.2.28
ICE BLOCK BLOCKAGE
DUCTED SCREW
HIGH PITCH, 0 M/S
Q (b, mean) - Q (o, mean)

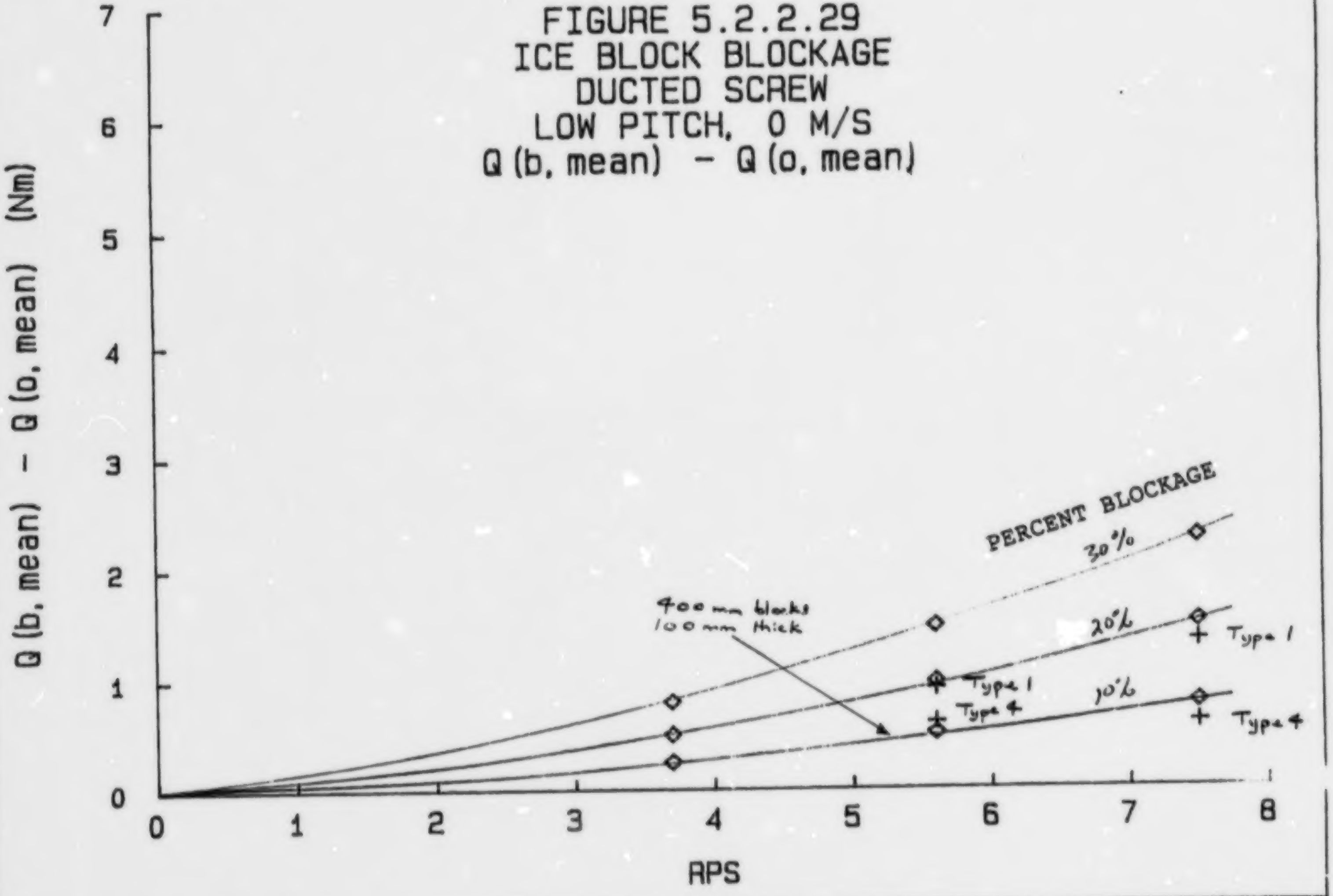


FIGURE 5.2.2.29
ICE BLOCK BLOCKAGE
DUCTED SCREW
LOW PITCH, 0 M/S
Q (b, mean) - Q (o, mean)

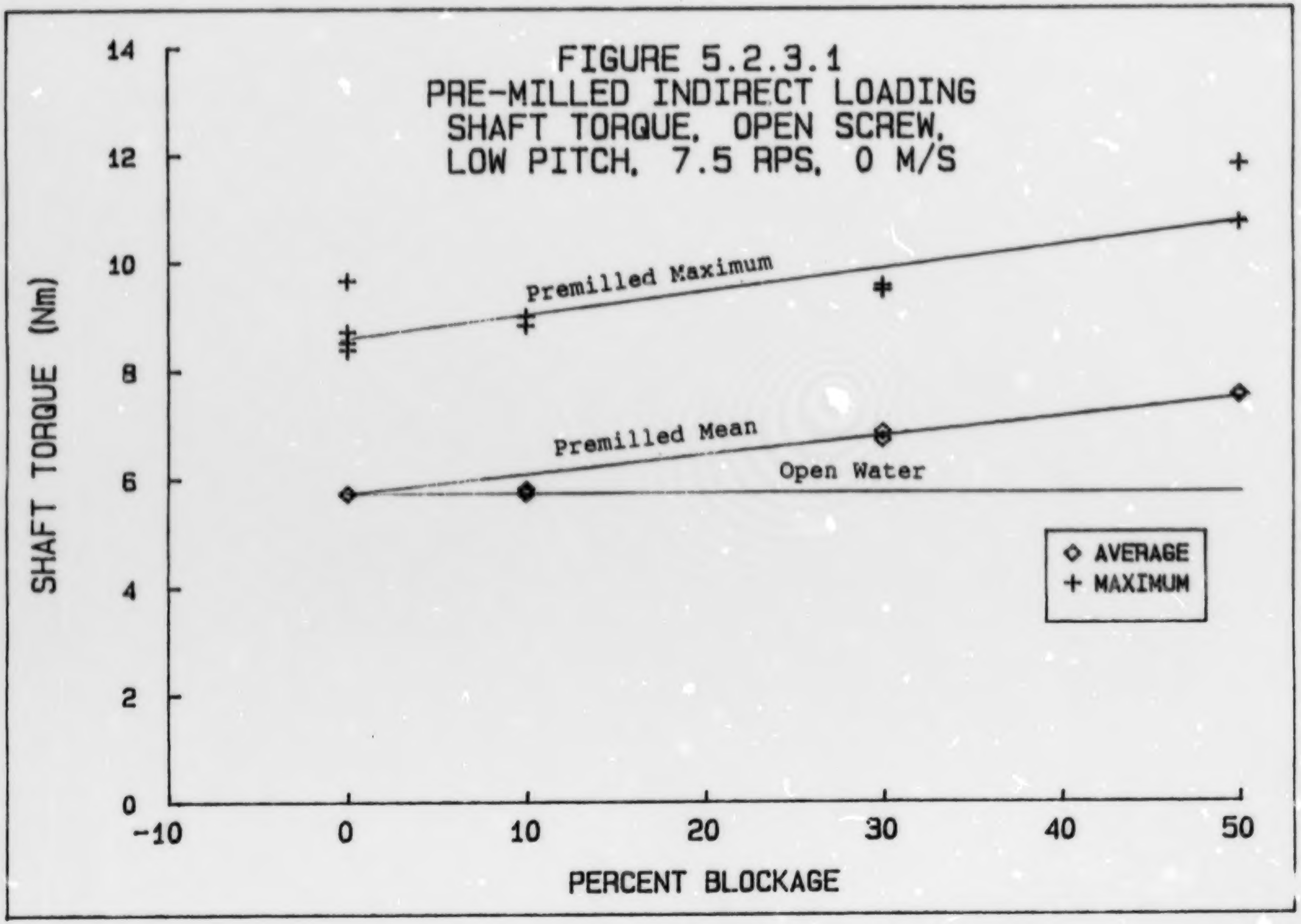


FIGURE 5.2.3.1
PRE-MILLED INDIRECT LOADING
SHAFT TORQUE, OPEN SCREW,
LOW PITCH, 7.5 RPS, 0 M/S

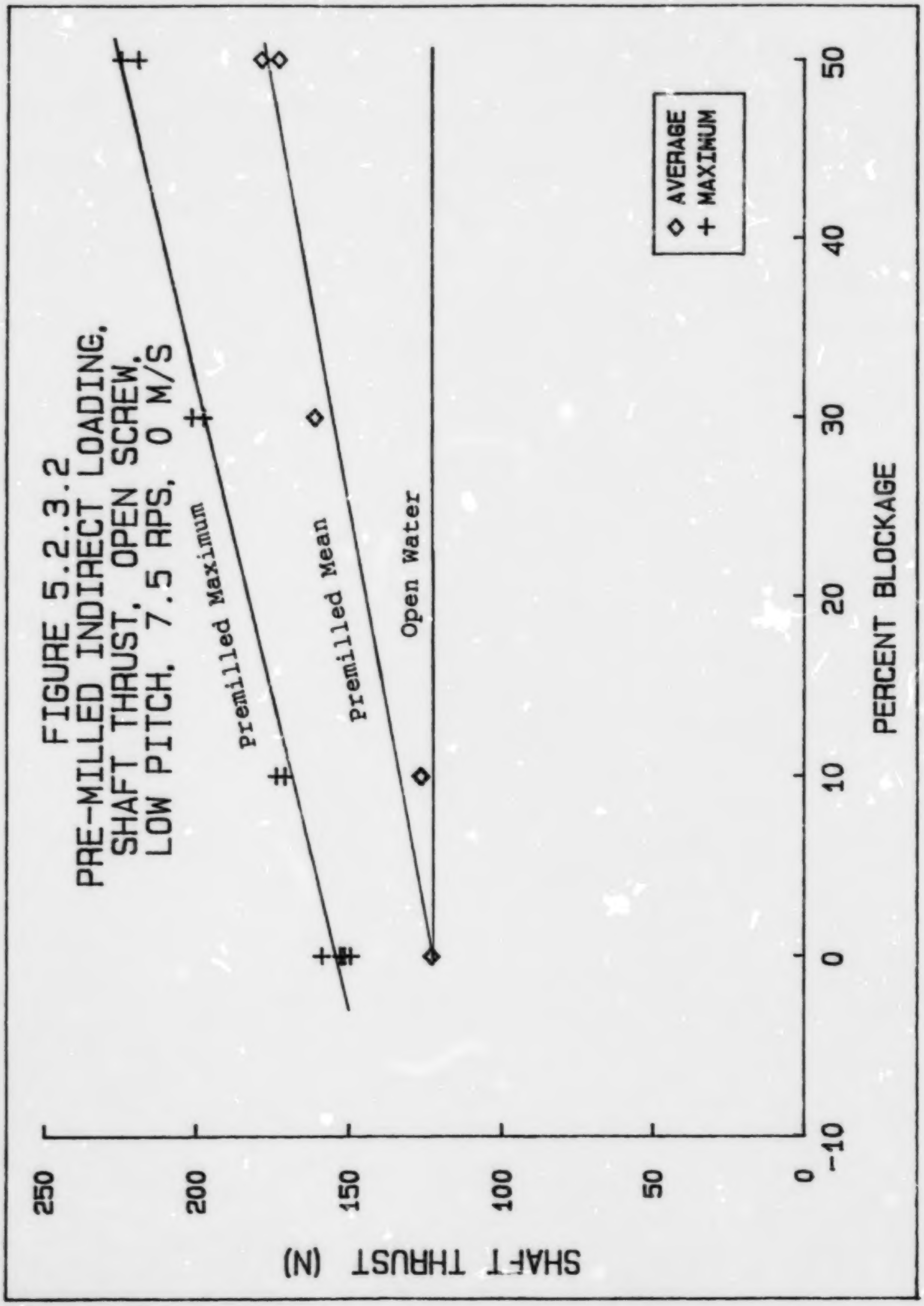


FIGURE 5.2.3.2
PRE-MILLED INDIRECT LOADING,
SHAFT THRUST, OPEN SCREW,
LOW PITCH, 7.5 RPS, 0 M/S

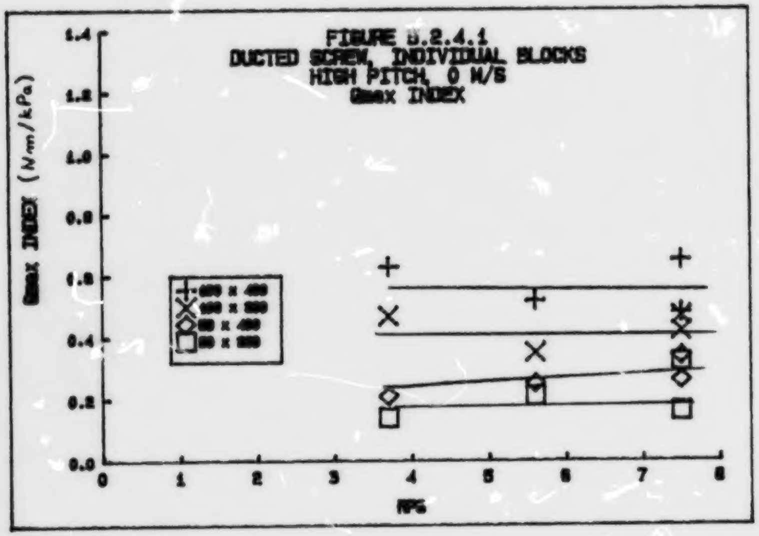


FIGURE 5.2.4.1
DUCTED SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 0 M/S
Gmax INDEX

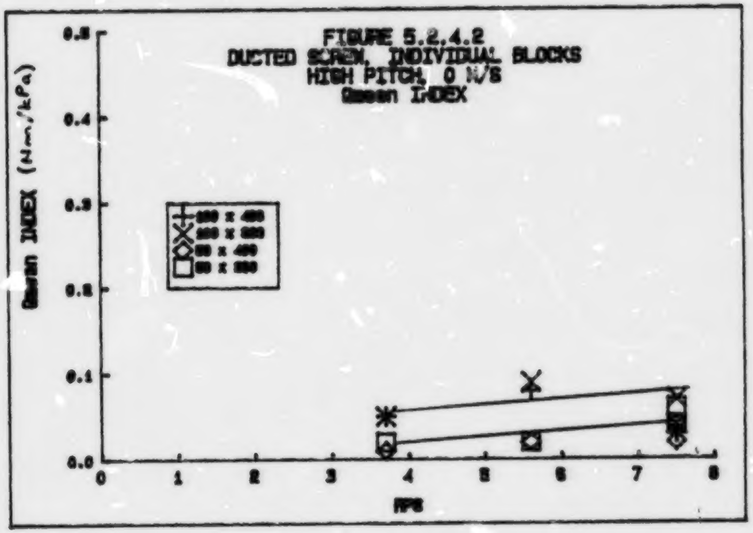


FIGURE 5.2.4.2
DUCTED SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 0 M/S
Gmean INDEX

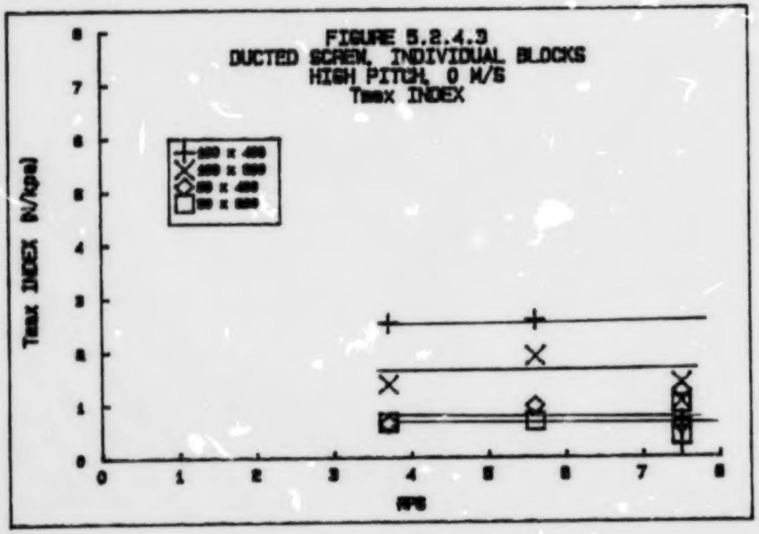


FIGURE 5.2.4.3
DUCTED SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 0 M/S
Tmax INDEX

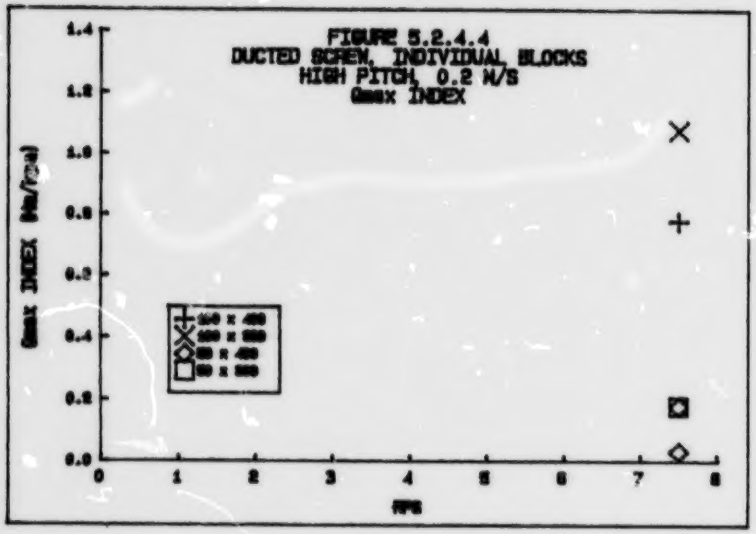


FIGURE 5.2.4.4
DUCTED SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 0.2 M/S
Gmax INDEX

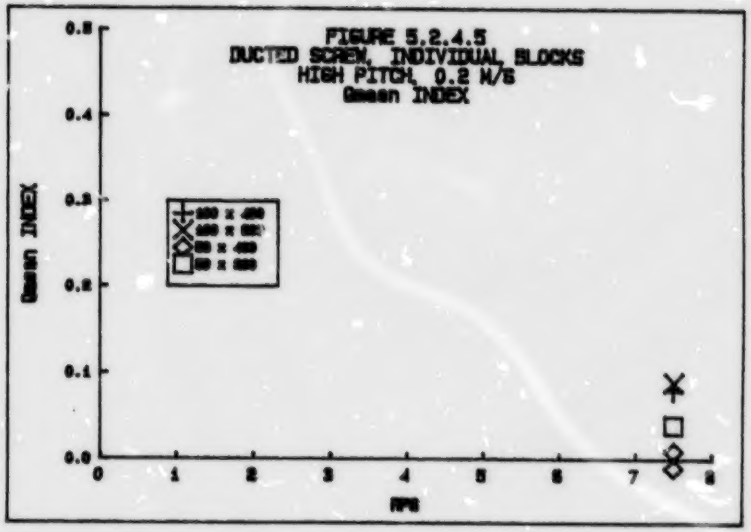


FIGURE 5.2.4.5
DUCTED SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 0.2 M/S
Gmean INDEX

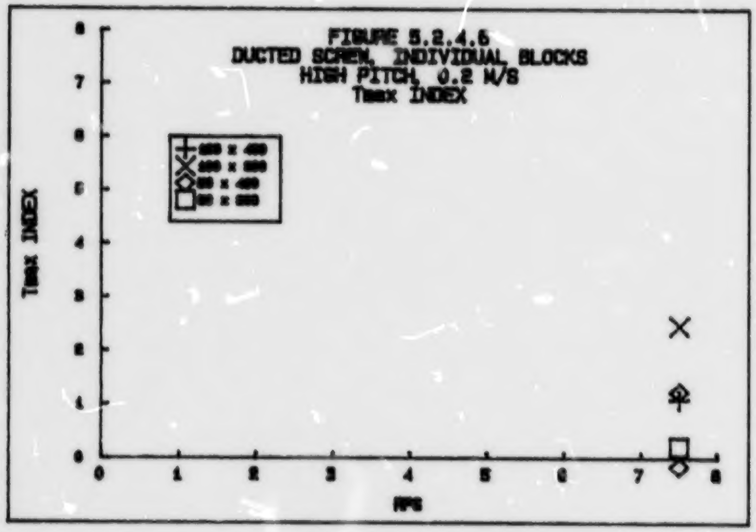


FIGURE 5.2.4.6
DUCTED SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 0.2 M/S
Tmax INDEX

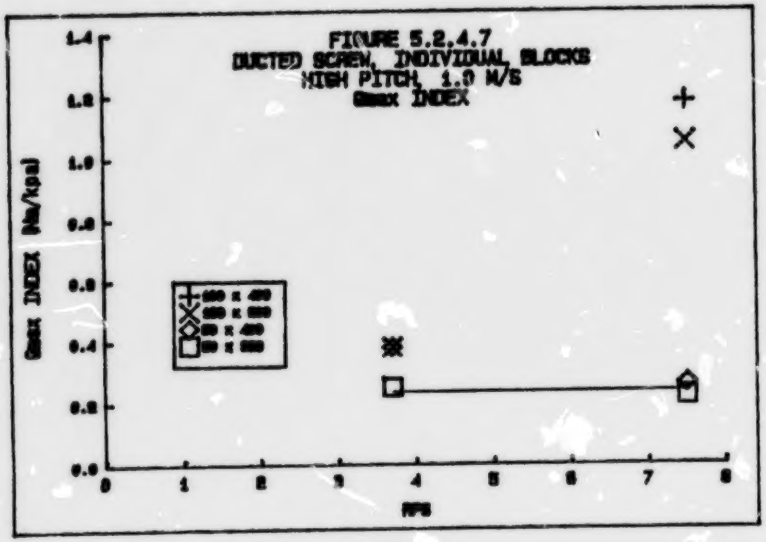


FIGURE 5.2.4.7
DUCTED SCREEN, INDIVIDUAL BLOCKS
HIGH PITCH, 1.0 M/S
Gmax INDEX

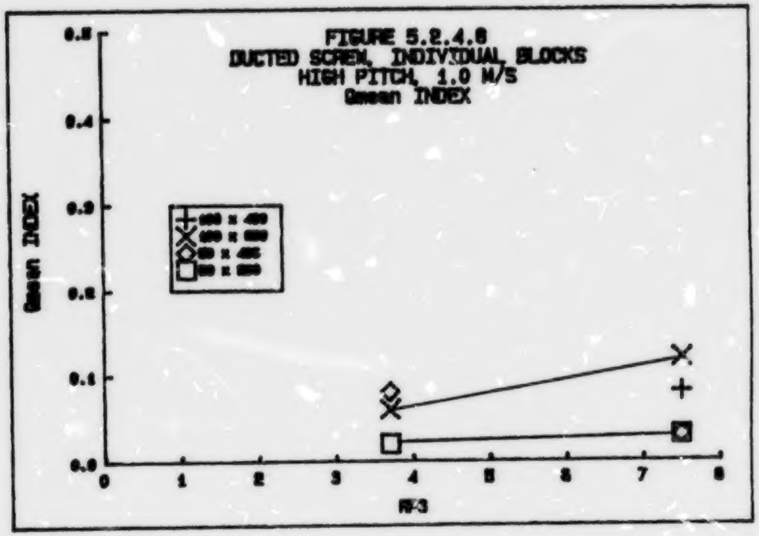


FIGURE 5.2.4.8
DUCTED SCREEN, INDIVIDUAL BLOCKS
HIGH PITCH, 1.0 M/S
Gmean INDEX

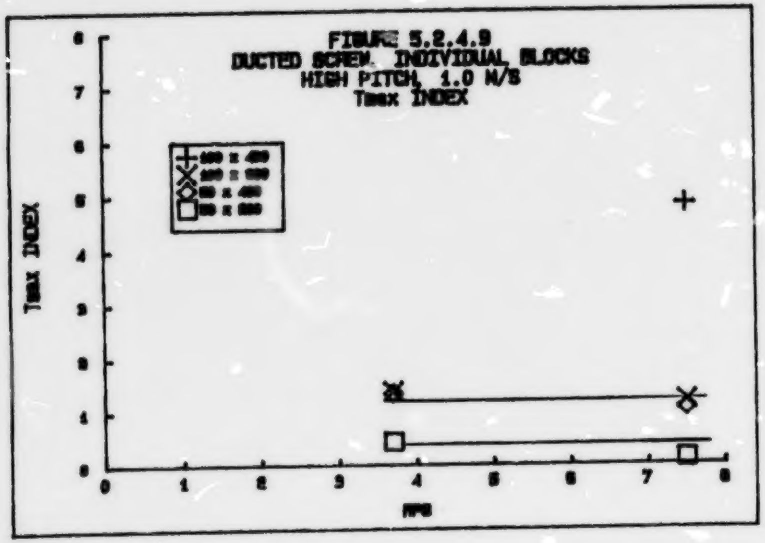


FIGURE 5.2.4.9
DUCTED SCREEN, INDIVIDUAL BLOCKS
HIGH PITCH, 1.0 M/S
Tmax INDEX

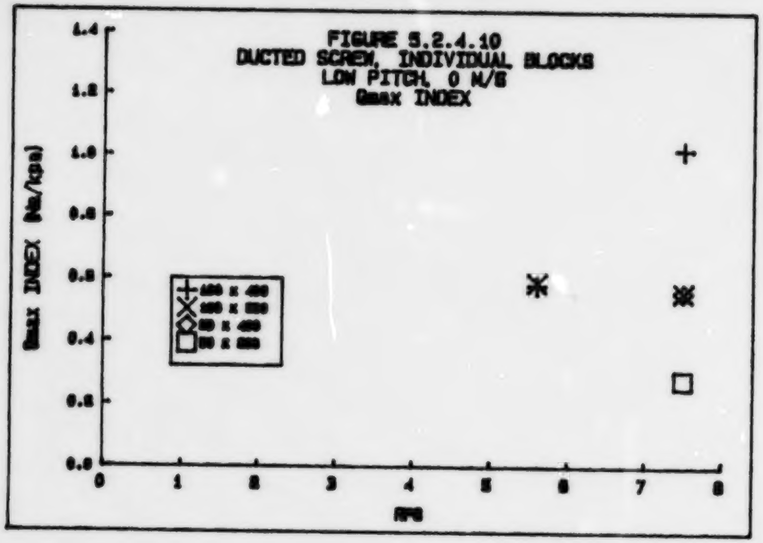


FIGURE 5.2.4.10
DUCTED SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 0 M/S
Qmax INDEX

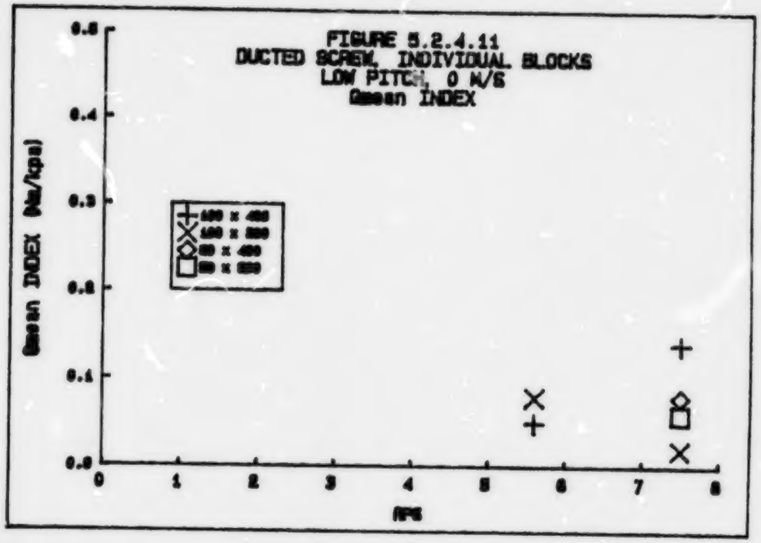


FIGURE 5.2.4.11
DUCTED SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 0 M/S
Qmean INDEX

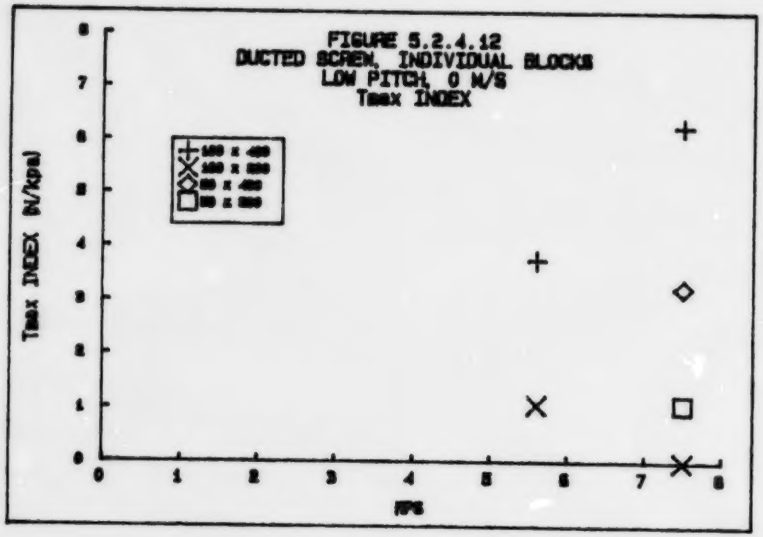


FIGURE 5.2.4.12
DUCTED SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 0 M/S
Tmax INDEX

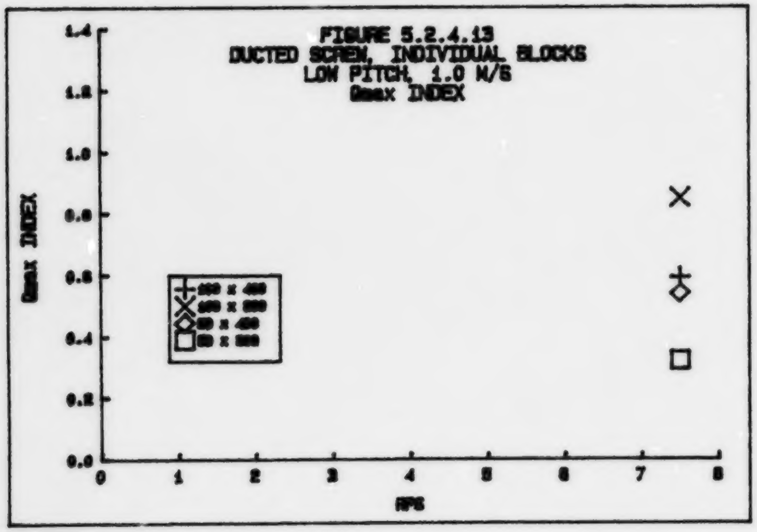


FIGURE 5.2.4.13
DUCTED SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 1.0 M/S
Qmax INDEX

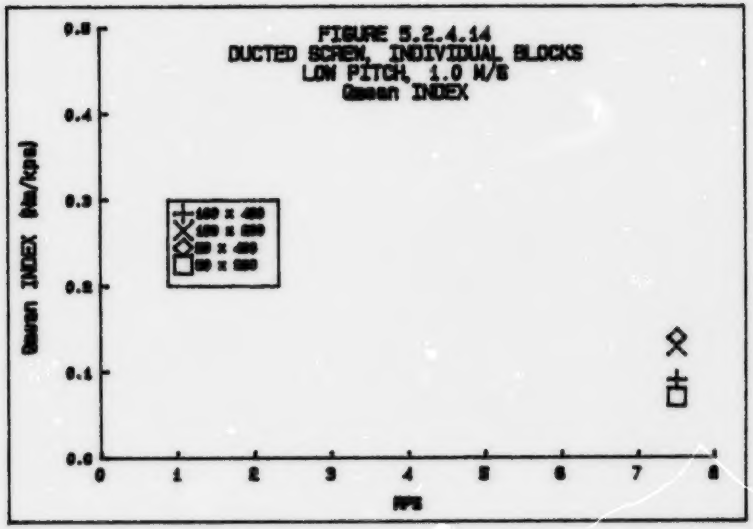


FIGURE 5.2.4.14
DUCTED SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 1.0 M/S
Qmean INDEX

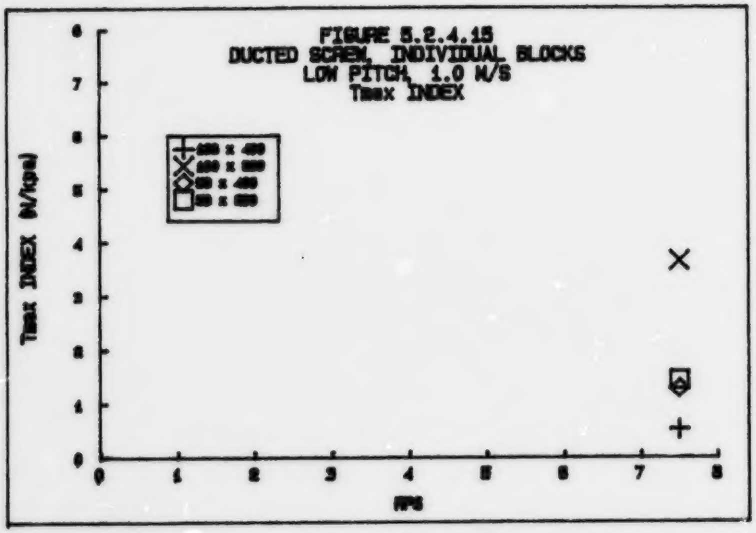


FIGURE 5.2.4.15
DUCTED SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 1.0 M/S
Tmax INDEX

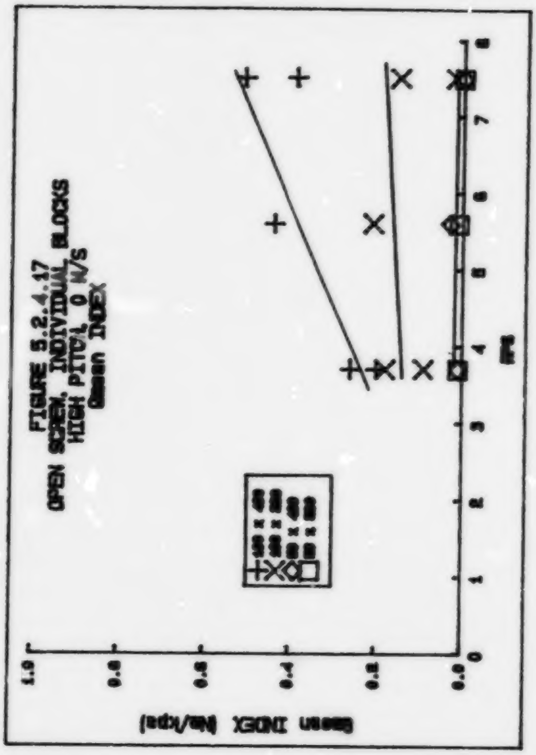


FIGURE 5.2.4.17
OPEN SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 0 M/S
Qmean INDEX

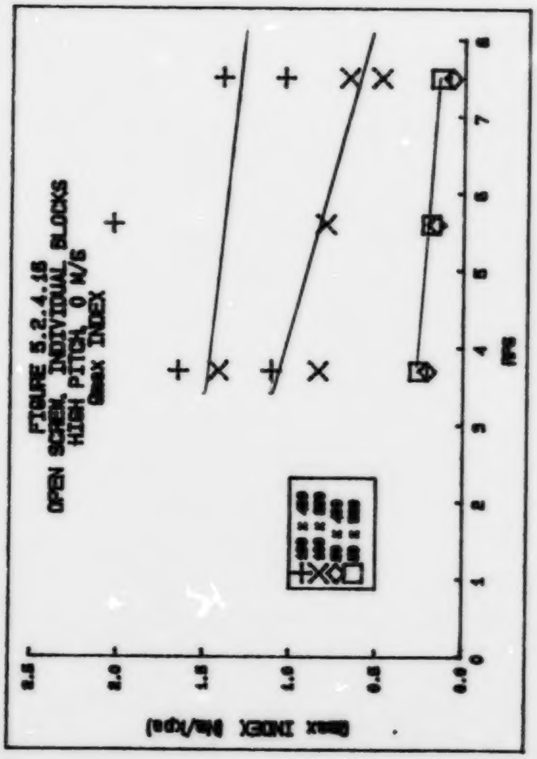


FIGURE 5.2.4.18
OPEN SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 0 M/S
Qmax INDEX

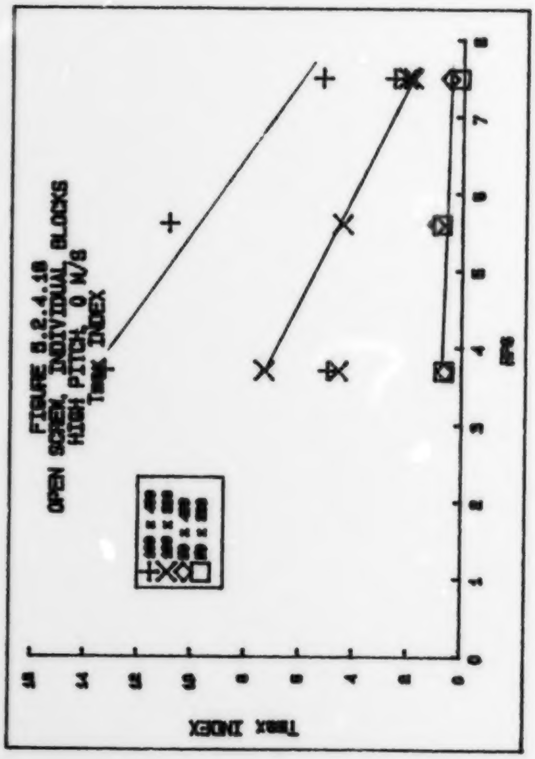


FIGURE 5.2.4.19
OPEN SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 0 M/S
Tmax INDEX

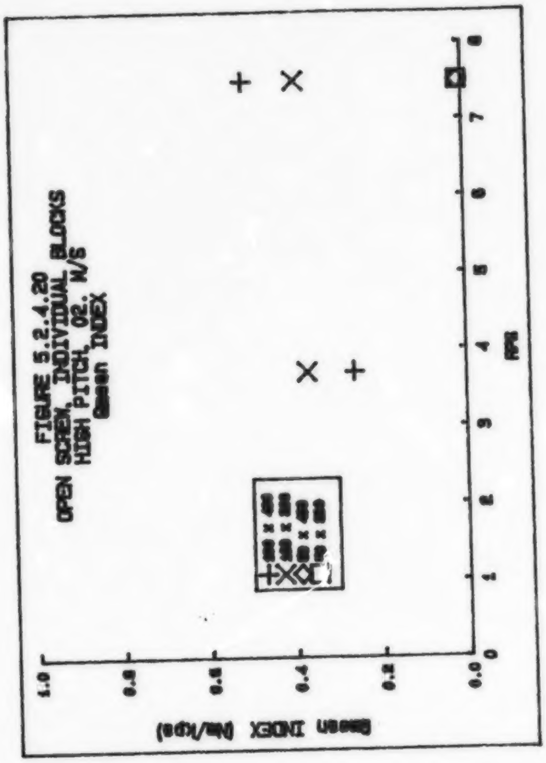


FIGURE 5.2.4.20
OPEN SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 02. N/S
Gmean INDEX

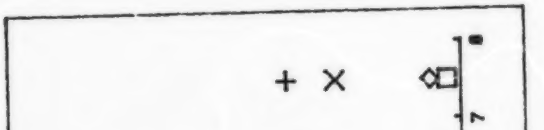


FIGURE 5.2.4.19
OPEN SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 02. N/S
Gmax INDEX

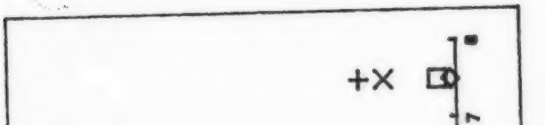


FIGURE 5.2.4.21
OPEN SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 02. N/S
Tmax INDEX

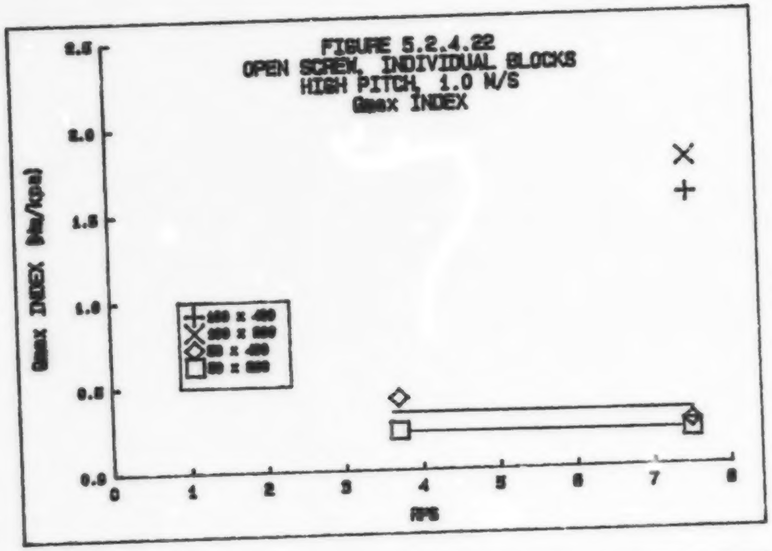


FIGURE 5.2.4.22
OPEN SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 1.0 M/S
Gmax INDEX

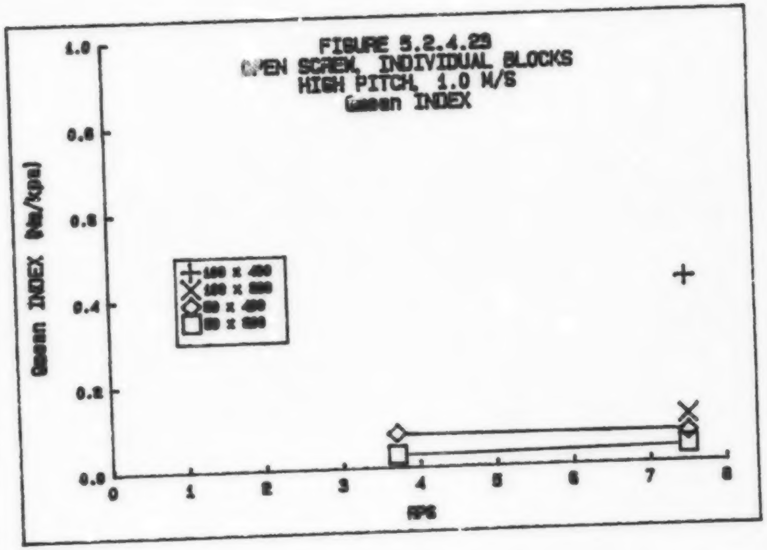


FIGURE 5.2.4.23
OPEN SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 1.0 M/S
Gmean INDEX

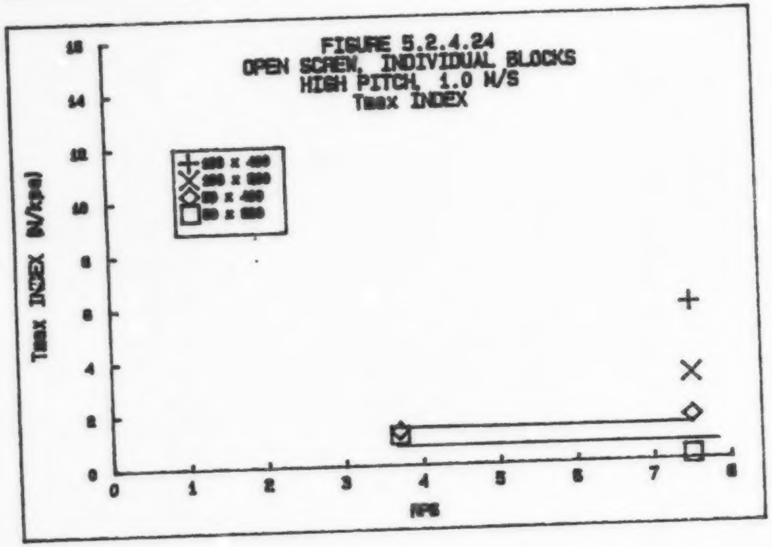


FIGURE 5.2.4.24
OPEN SCREW, INDIVIDUAL BLOCKS
HIGH PITCH, 1.0 M/S
Tmax INDEX

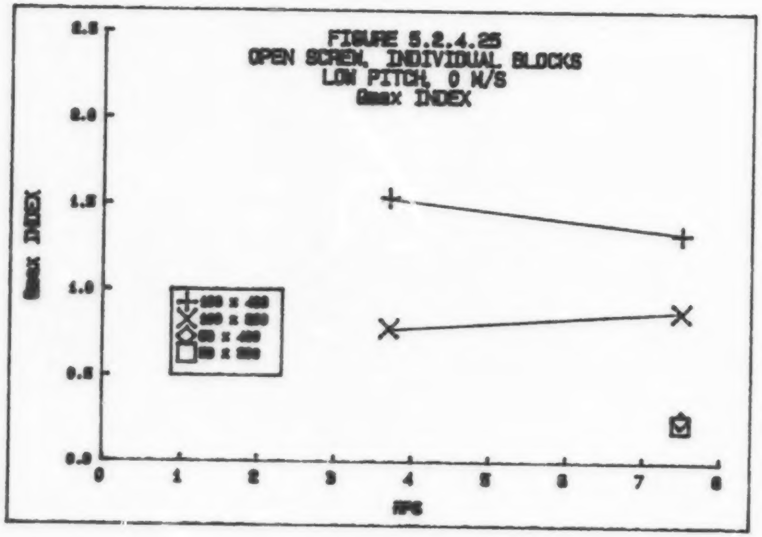


FIGURE 5.2.4.25
OPEN SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 0 M/S
Qmax INDEX

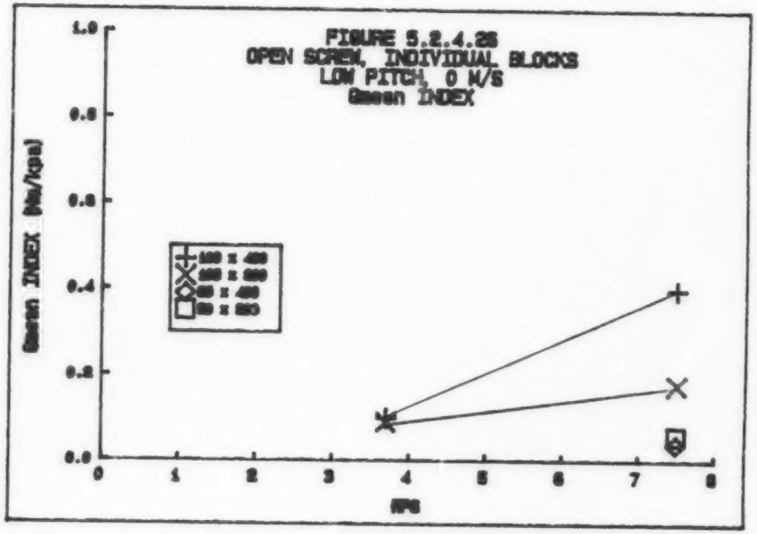


FIGURE 5.2.4.26
OPEN SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 0 M/S
Qmean INDEX

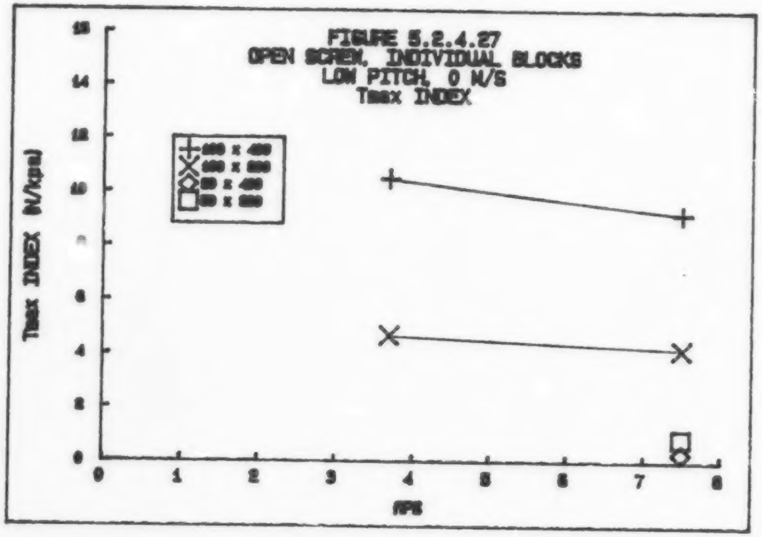


FIGURE 5.2.4.27
OPEN SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 0 M/S
Tmax INDEX

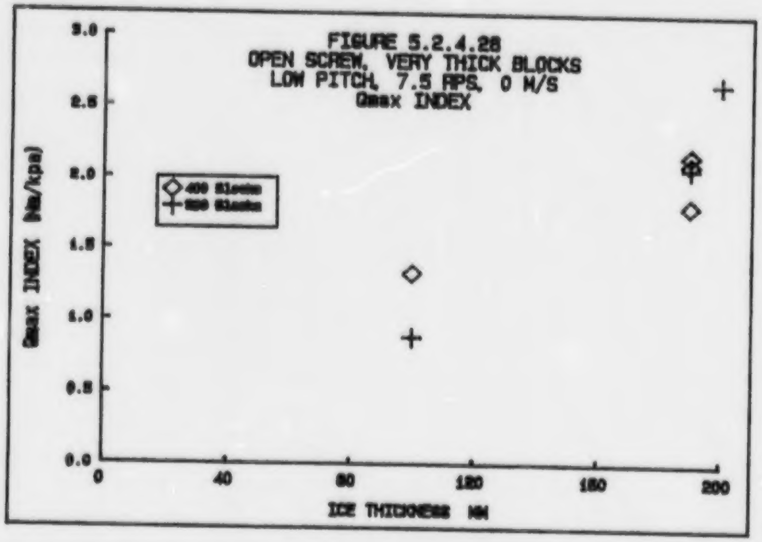


FIGURE 5.2.4.28
OPEN SCREW, VERY THICK BLOCKS
LOW PITCH, 7.5 RPS, 0 M/S
Qmax INDEX

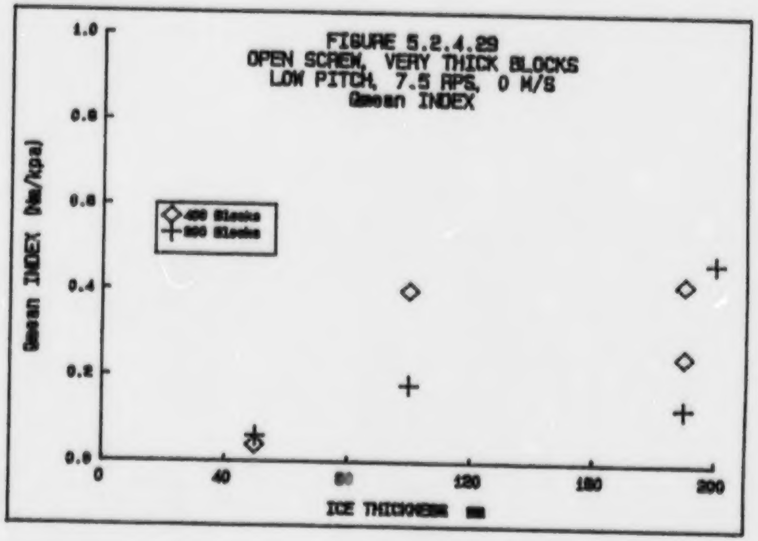


FIGURE 5.2.4.29
OPEN SCREW, VERY THICK BLOCKS
LOW PITCH, 7.5 RPS, 0 M/S
Qmean INDEX

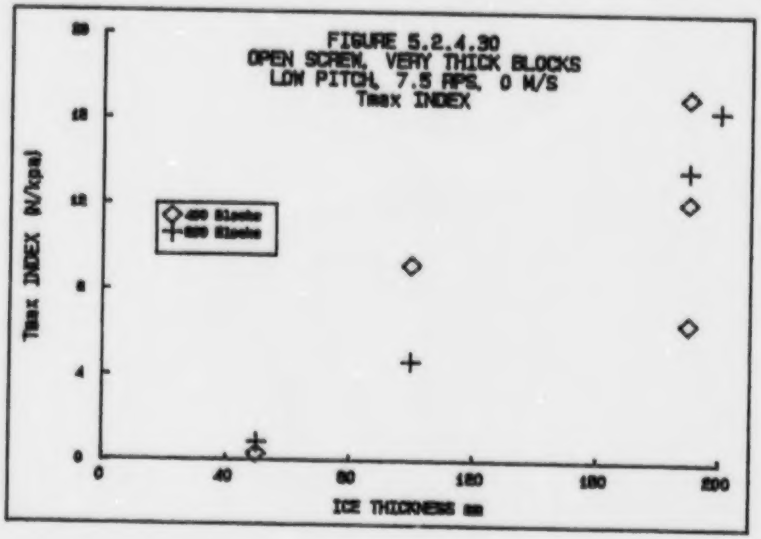


FIGURE 5.2.4.30
OPEN SCREW, VERY THICK BLOCKS
LOW PITCH, 7.5 RPS, 0 M/S
Tmax INDEX

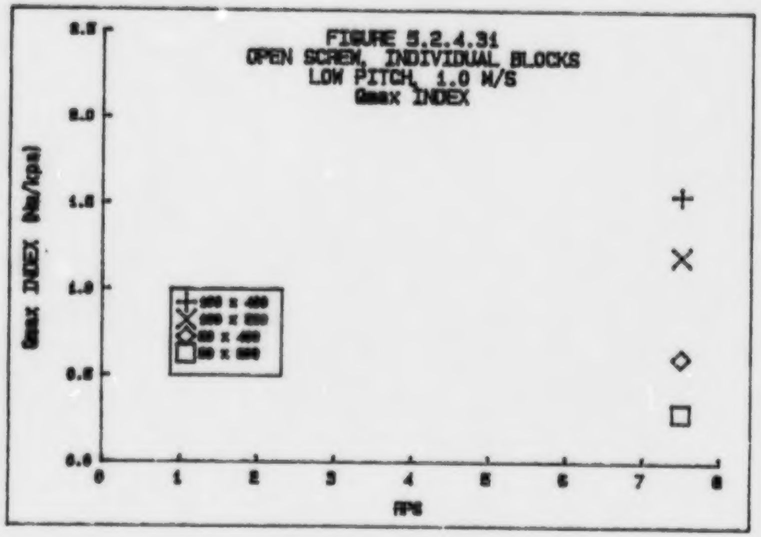


FIGURE 5.2.4.31
OPEN SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 1.0 M/S
Qmax INDEX

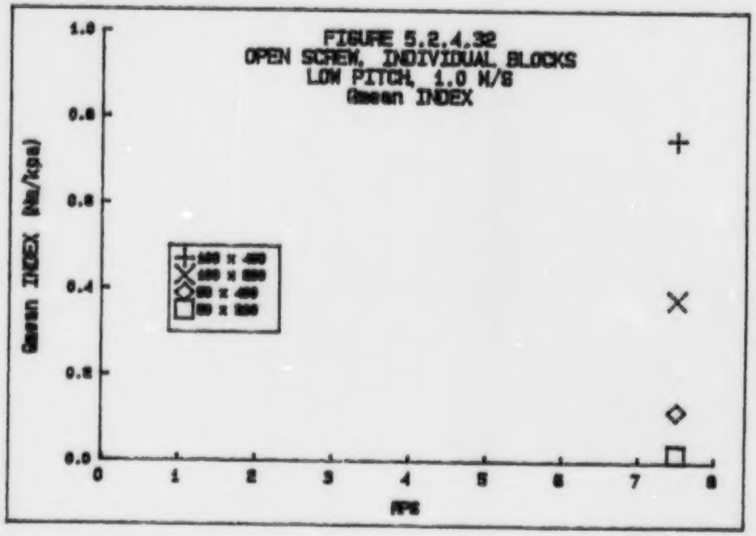


FIGURE 5.2.4.32
OPEN SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 1.0 M/S
Qmean INDEX

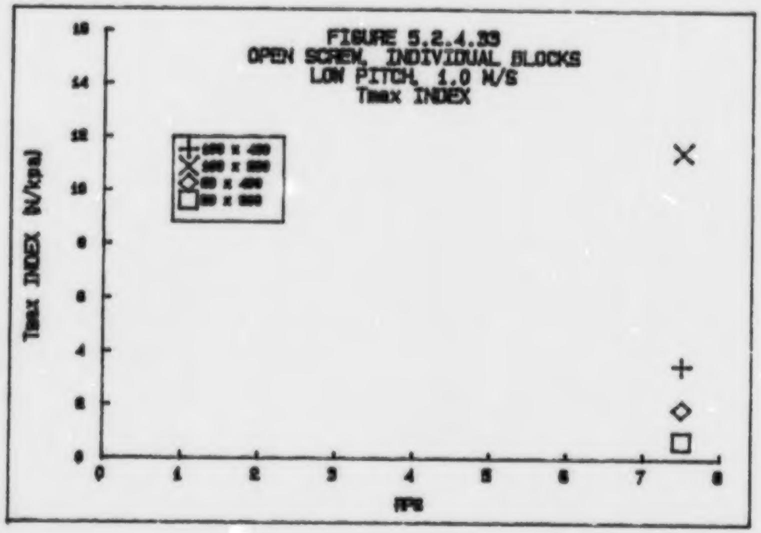


FIGURE 5.2.4.33
OPEN SCREW, INDIVIDUAL BLOCKS
LOW PITCH, 1.0 M/S
Tmax INDEX

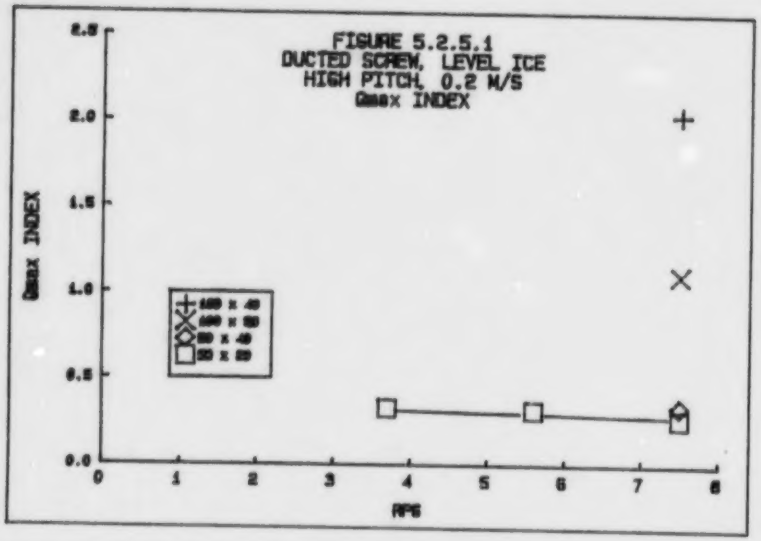


FIGURE 5.2.5.1
DUCTED SCREW, LEVEL ICE
HIGH PITCH, 0.2 M/S
Qmax INDEX

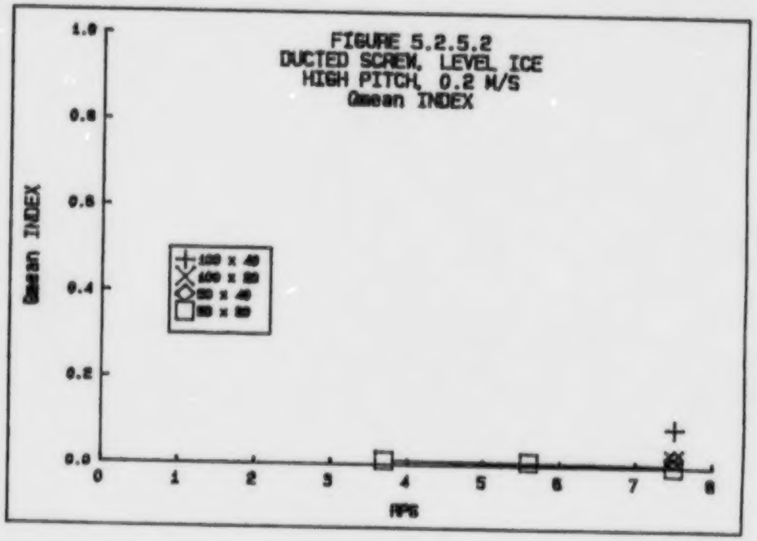


FIGURE 5.2.5.2
DUCTED SCREW, LEVEL ICE
HIGH PITCH, 0.2 M/S
Qmean INDEX

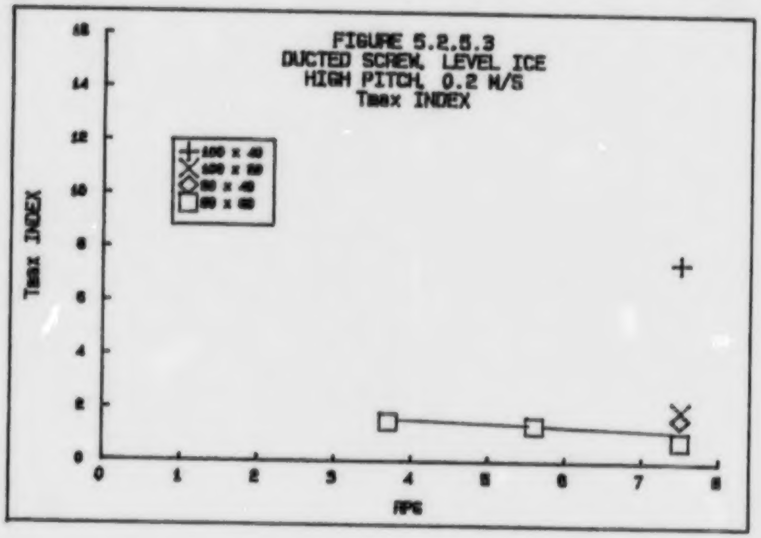


FIGURE 5.2.5.3
DUCTED SCREW, LEVEL ICE
HIGH PITCH, 0.2 M/S
Tmax INDEX

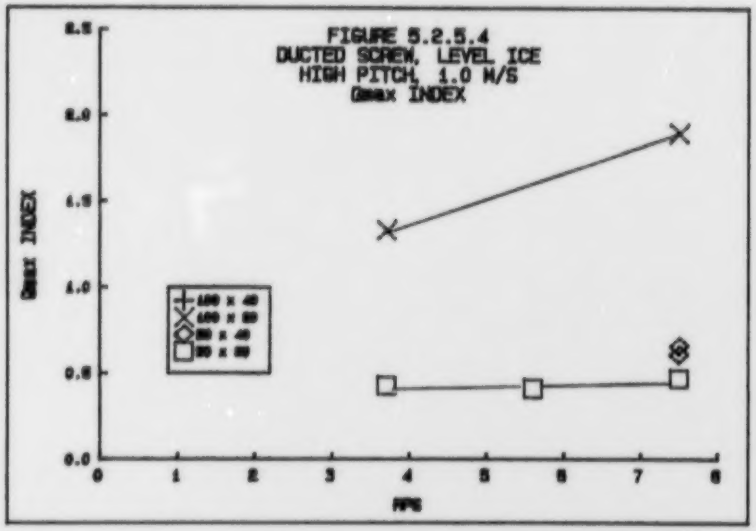


FIGURE 5.2.5.4
DUCTED SCREW, LEVEL ICE
HIGH PITCH, 1.0 M/S
Qmax INDEX

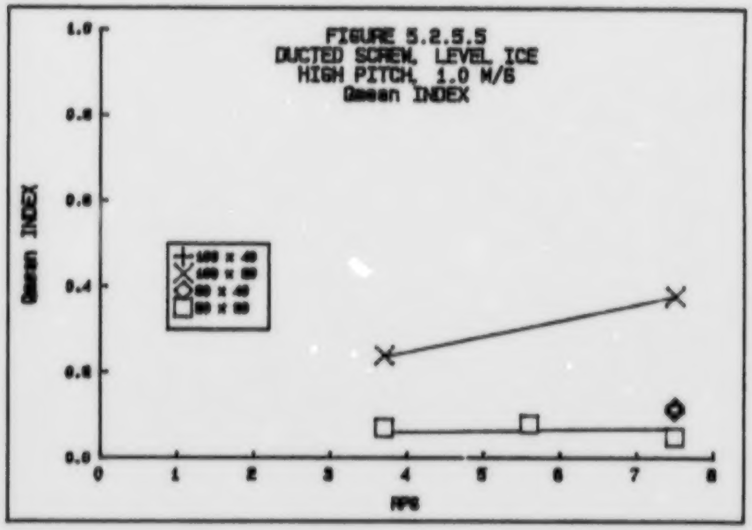


FIGURE 5.2.5.5
DUCTED SCREW, LEVEL ICE
HIGH PITCH, 1.0 M/S
Qmean INDEX

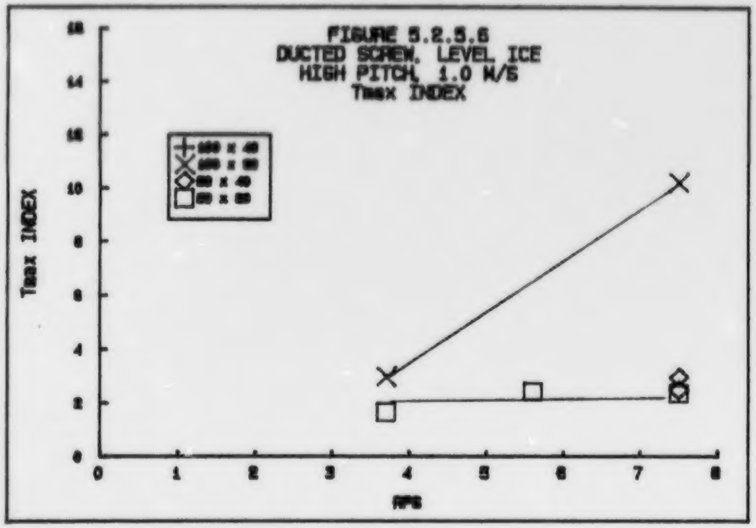


FIGURE 5.2.5.6
DUCTED SCREW, LEVEL ICE
HIGH PITCH, 1.0 M/S
Tmax INDEX

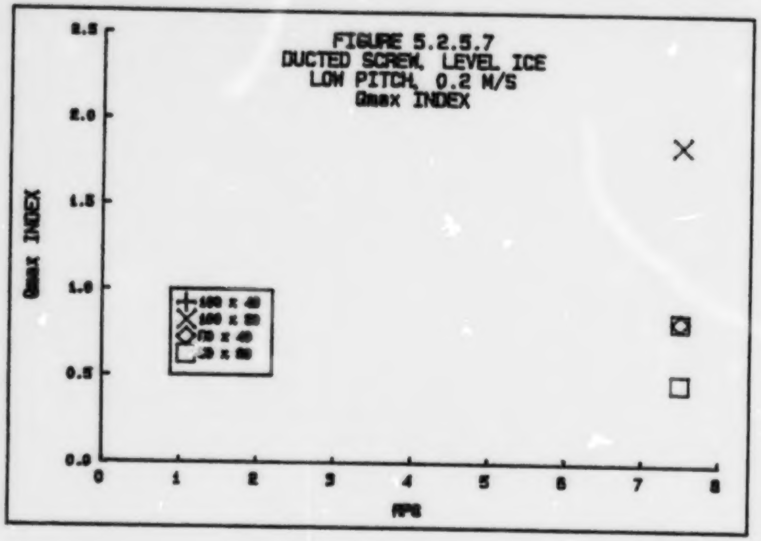


FIGURE 5.2.5.7
DUCTED SCREW, LEVEL ICE
LOW PITCH, 0.2 M/S
Gmax INDEX

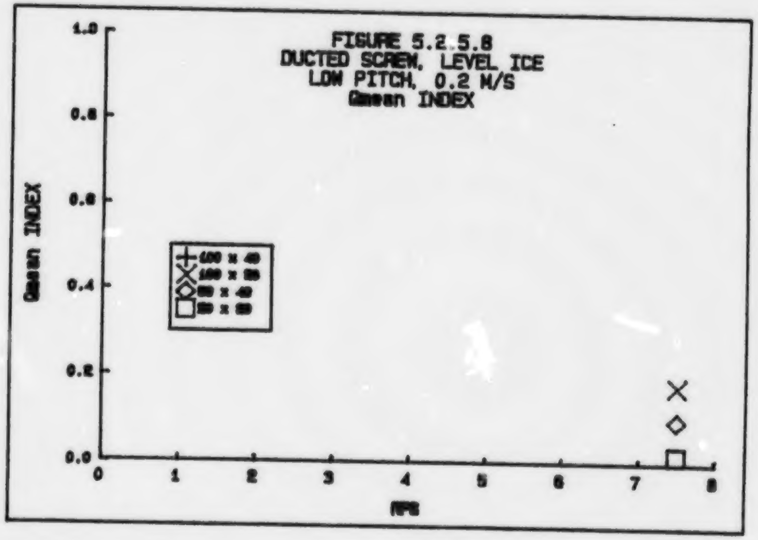


FIGURE 5.2.5.8
DUCTED SCREW, LEVEL ICE
LOW PITCH, 0.2 M/S
Gmean INDEX

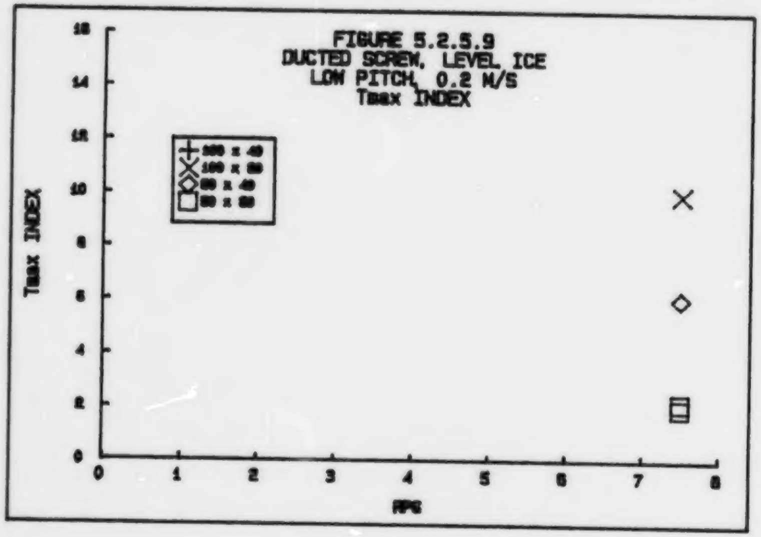


FIGURE 5.2.5.9
DUCTED SCREW, LEVEL ICE
LOW PITCH, 0.2 M/S
Tmax INDEX

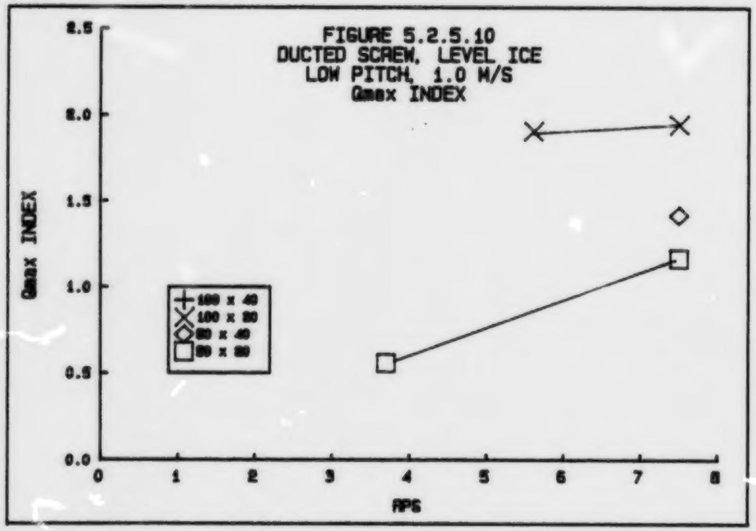


FIGURE 5.2.5.10
DUCTED SCREW, LEVEL ICE
LOW PITCH, 1.0 M/S
Gmax INDEX

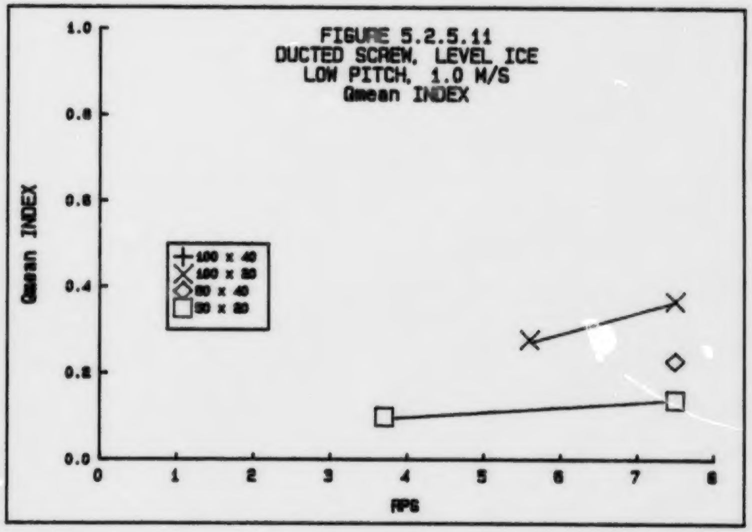


FIGURE 5.2.5.11
DUCTED SCREW, LEVEL ICE
LOW PITCH, 1.0 M/S
Gmean INDEX

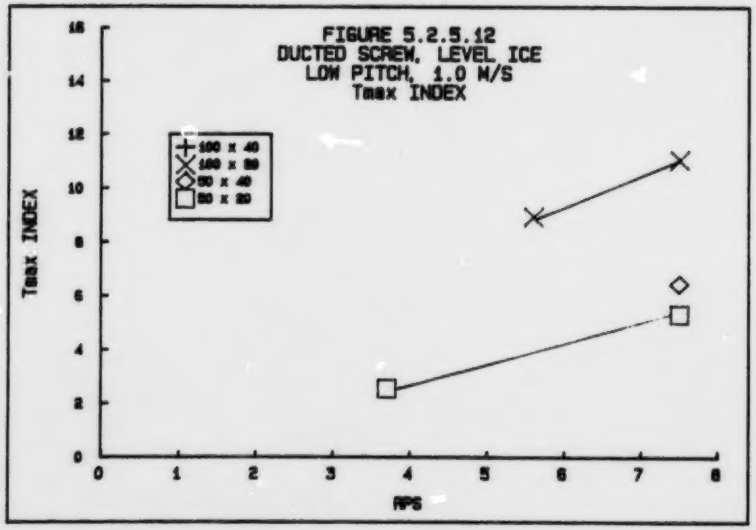


FIGURE 5.2.5.12
DUCTED SCREW, LEVEL ICE
LOW PITCH, 1.0 M/S
Tmax INDEX

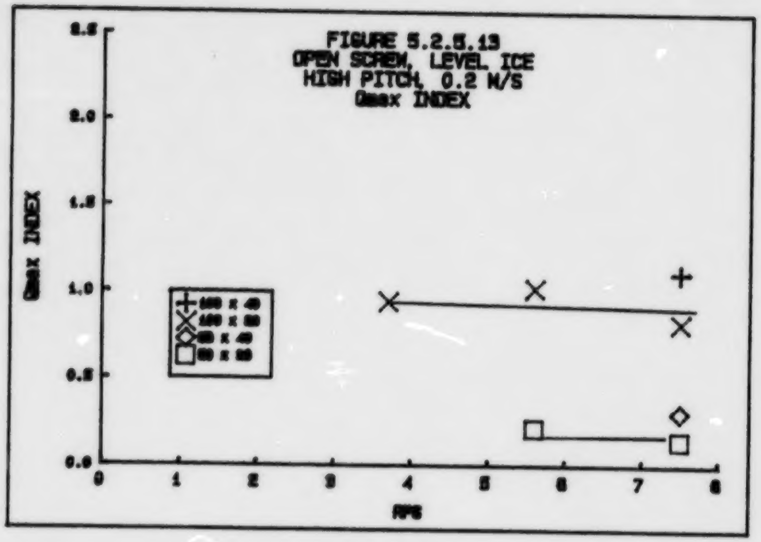


FIGURE 5.2.5.13
OPEN SCREW, LEVEL ICE
HIGH PITCH, 0.2 M/S
Qmax INDEX

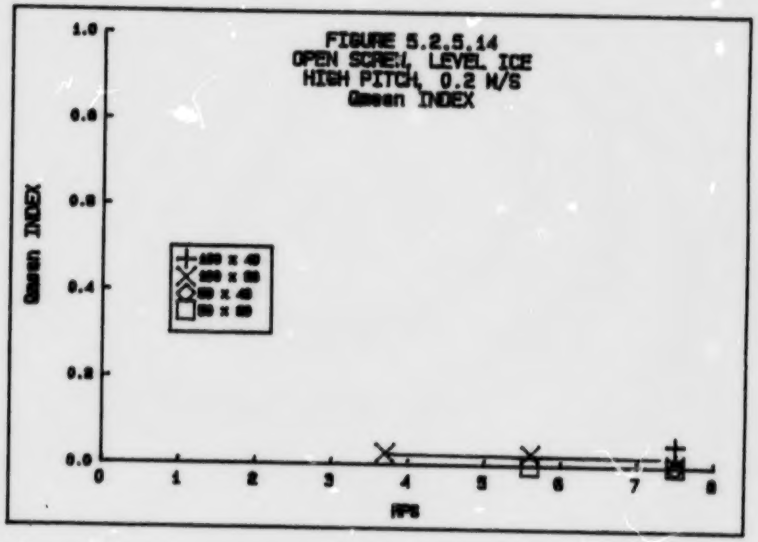


FIGURE 5.2.5.14
OPEN SCREW, LEVEL ICE
HIGH PITCH, 0.2 M/S
Qmean INDEX

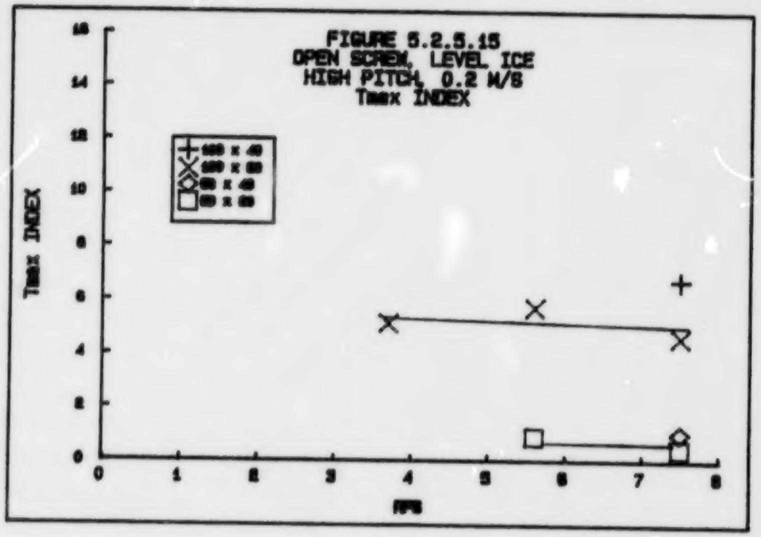


FIGURE 5.2.5.15
OPEN SCREW, LEVEL ICE
HIGH PITCH, 0.2 M/S
Tmax INDEX

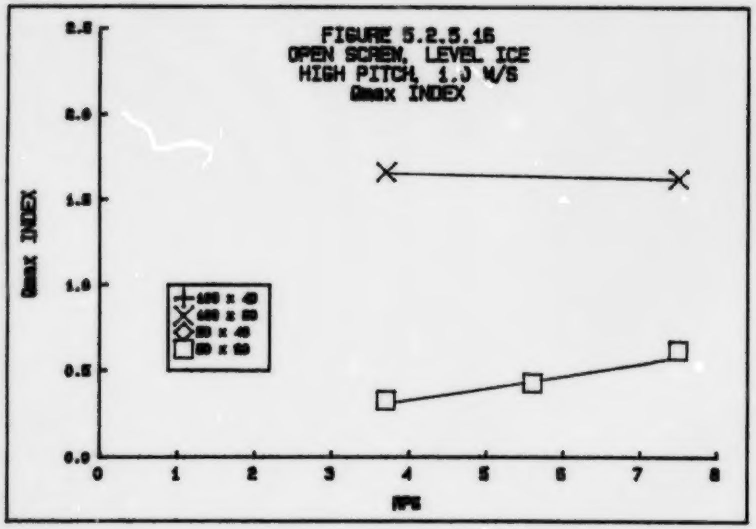


FIGURE 5.2.5.16
OPEN SCREEN, LEVEL ICE
HIGH PITCH, 1.0 M/S
Qmax INDEX

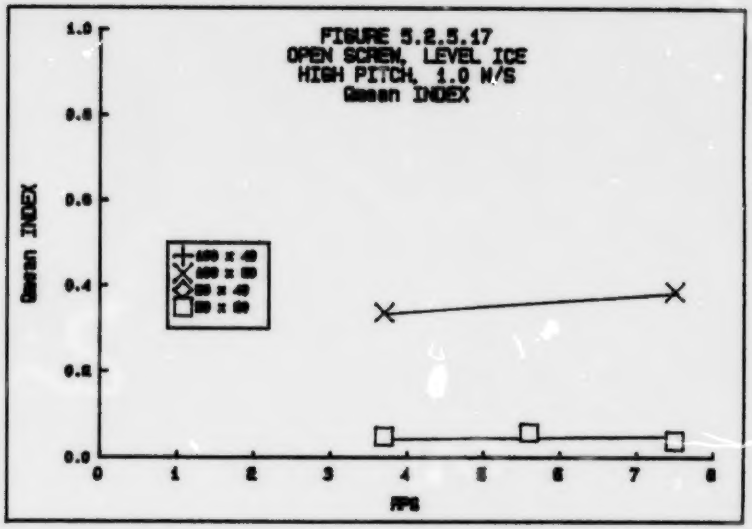


FIGURE 5.2.5.17
OPEN SCREEN, LEVEL ICE
HIGH PITCH, 1.0 M/S
Qmean INDEX

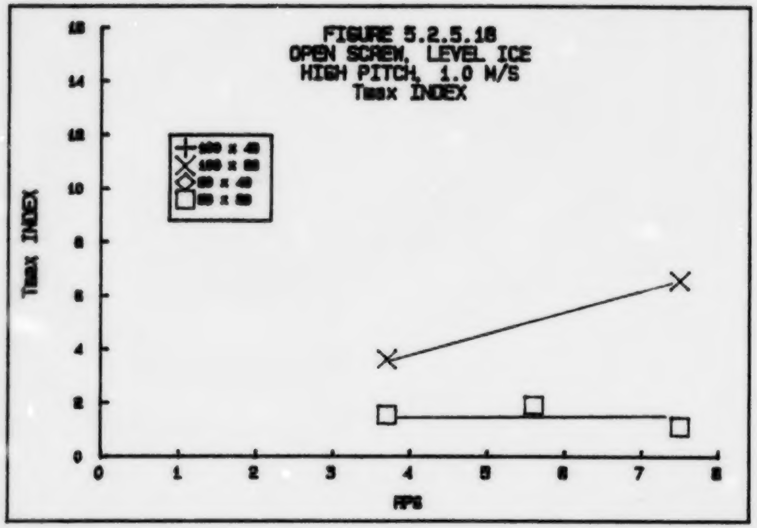


FIGURE 5.2.5.18
OPEN SCREEN, LEVEL ICE
HIGH PITCH, 1.0 M/S
Tmax INDEX

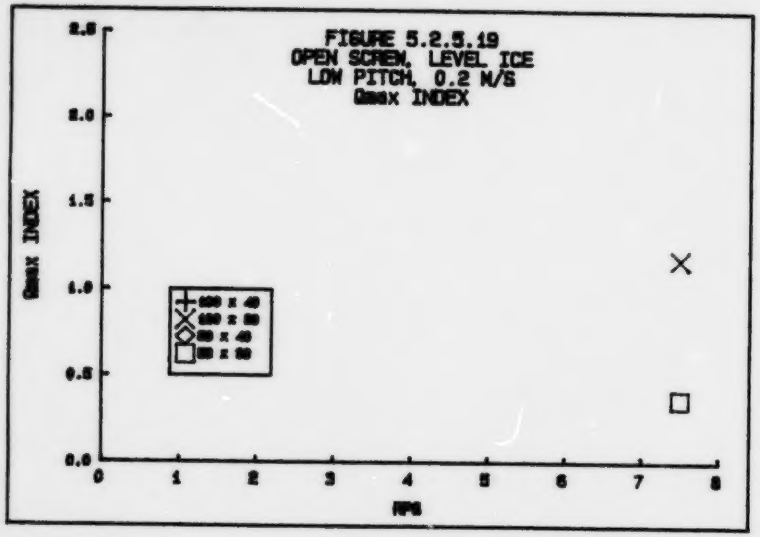


FIGURE 5.2.5.19
OPEN SCREW, LEVEL ICE
LOW PITCH, 0.2 M/S
Qmax INDEX

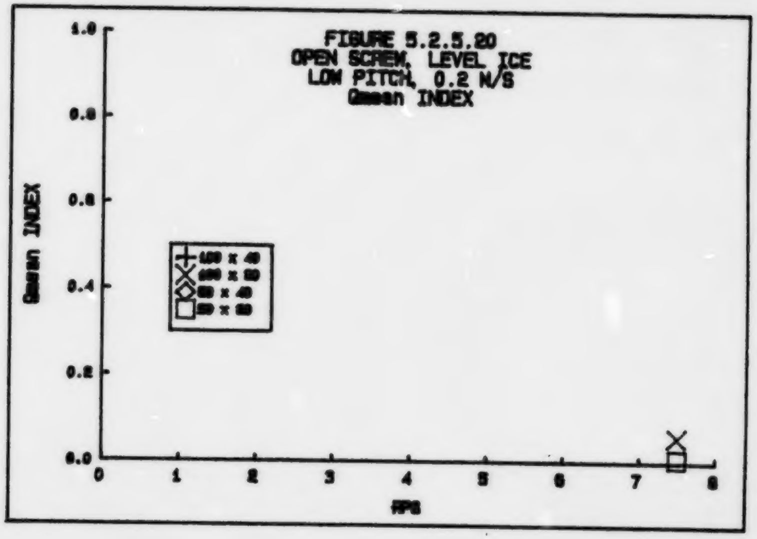


FIGURE 5.2.5.20
OPEN SCREW, LEVEL ICE
LOW PITCH, 0.2 M/S
Qmean INDEX

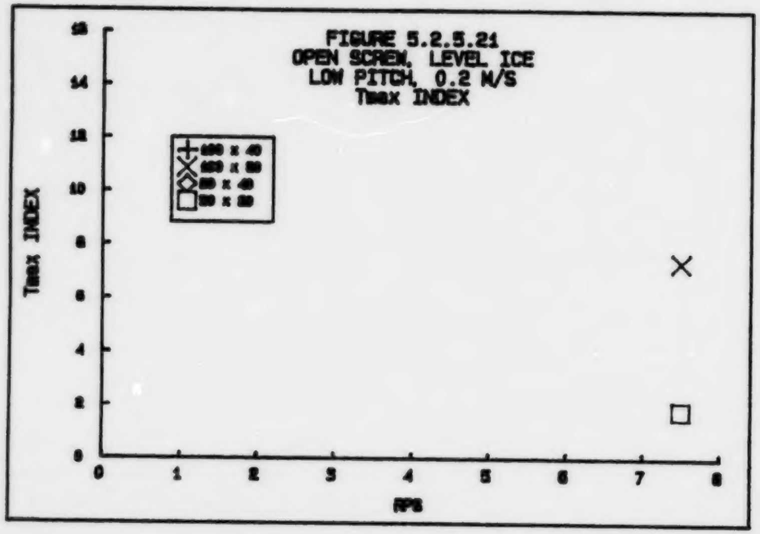


FIGURE 5.2.5.21
OPEN SCREW, LEVEL ICE
LOW PITCH, 0.2 M/S
Tmax INDEX

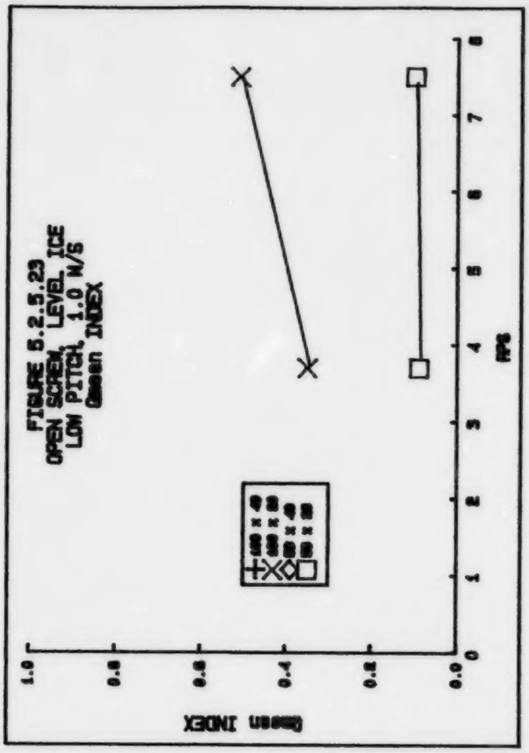


FIGURE 5.2.5.23
OPEN SCREW, LEVEL ICE
LOW PITCH, 1.0 M/S
Qmean INDEX

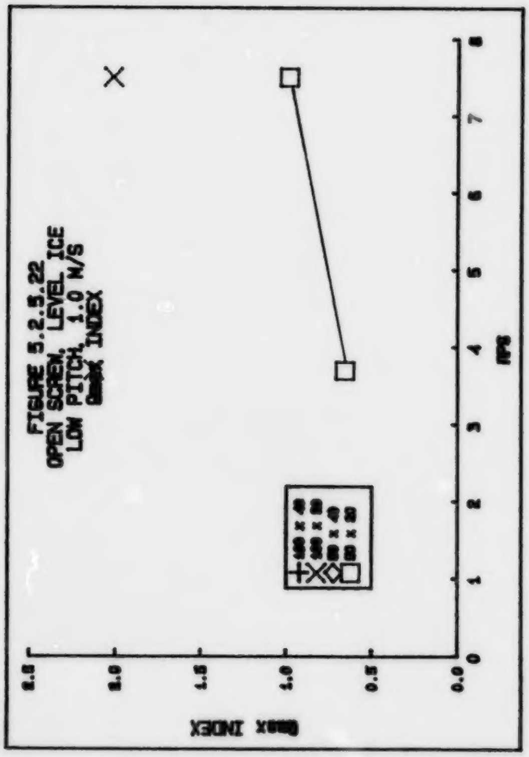


FIGURE 5.2.5.22
OPEN SCREW, LEVEL ICE
LOW PITCH, 1.0 M/S
Qmax INDEX

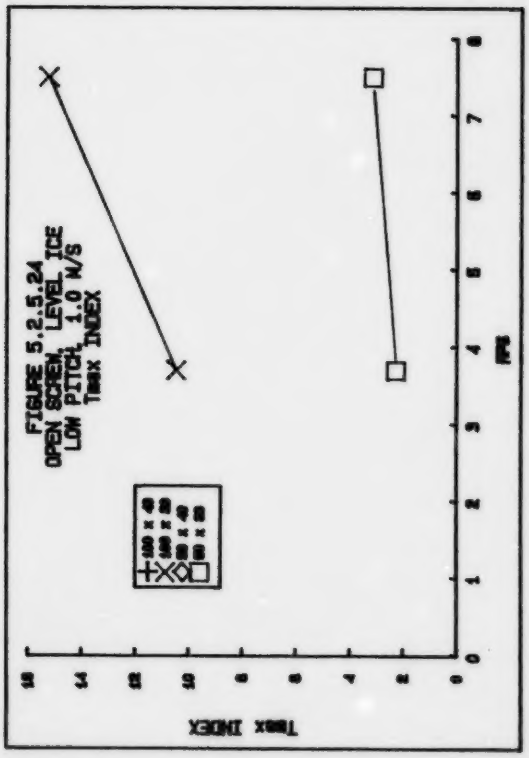


FIGURE 5.2.5.24
OPEN SCREW, LEVEL ICE
LOW PITCH, 1.0 M/S
Tmax INDEX

TABLE 3.1. Test Matrix OPEN PROPELLER

VELOCITY	0.0						0.2						1.0					
RPS	3.7		5.6		7.5		3.7		5.6		7.5		3.7		5.6		7.5	
PITCH	l	h	l	h	l	h	l	h	l	h	l	h	l	h	l	h	l	h
blocks																		
100x400	X	X		X	X	X		X				X					X	X
100x200	X	X		X	X	X		X				X					X	X
100x100	X	X		X	X	X		X				X					X	X
50x400		X		X	X	X						X		X			X	X
50x200		X		X	X	X						X		X			X	X
50x100		X		X	X	X						X		X			X	X
level ice																		
100x40												X						
100x20								X		X	X	X	X				X	X
50x60												X						
50x40												X						
50x20										X	X	X	X	X		X	X	X
blocks																		
200x200					X													
190x400					X													
190x200					X													
160x400					X													
160x200					X													
premilled																		
50%					X													
30%					X													
10%					X													

TABLE 3.1. Test Matrix NOZZLED PROPELLER

VELOCITY	0.0						0.2						1.0					
RPS	3.7		5.6		7.5		3.7		5.6		7.5		3.7		5.6		7.5	
PITCH	l	h	l	h	l	h	l	h	l	h	l	h	l	h	l	h	l	h
blocks																		
100x400		X	X	X	X	X						X		X			X	X
100x200		X	X	X	X	X						X		X			X	X
100x100		X	X	X	X	X						X		X				X
50x400		X		X	X	X						X		X			X	X
50x200		X		X	X	X						X		X			X	X
50x100		X		X	X	X						X		X			X	X
level ice																		
100x40												X						
100x20											X	X		X	X		X	X
50x60																		
50x40											X	X					X	X
50x20								X		X	X	X	X	X		X	X	X
presawn																		
100x200												X						
100x100												X						
blockage																		
30%	X	X	X	X	X	X												
10%		X		X	X	X												

TABLE 4.1. List of Tests

Day	Ice Th.	Run Nr.	Run Type	rpm	V	pitch	nozzle	Block Size	Sigma	Time Start	Time End
	mm			RPS	m/s	deg.	y/n	mm	kPa	s	s
2	100	2	icefree	7.5	0	h	y	n/a	0	3.2	35.3
2	100	3	icefree	5.6	0	h	y	n/a	0	1.4	20
2	100	4	icefree	3.7	0	h	y	n/a	0	1.2	14.6
2	100	5	blockage	3.7	0	h	y	10 %	0	1.8	30.2
2	100	6	blockage	5.6	0	h	y	10 %	0	2.7	27.3
2	100	7	blockage	7.5	0	h	y	10 %	0	2.3	24.9
2	100	8	blockage	7.5	0	h	y	30 %	0	1.1	16.2
2	100	9	blockage	5.6	0	h	y	30 %	0	0.7	7.8
2	100	10	blockage	3.7	0	h	y	30 %	0	1	14.9
2	100	11	blocks	3.7	0	h	y	100		15.68	16.62
2	100	11	icefree	3.7	0	h	y	n/a	0	28.94	76.12
2	100	11	blocks	3.7	0	h	y	200		85.5	108.64
2	100	11	blocks	3.7	0	h	y	200		134.44	187.18
2	100	11	blocks	3.7	0	h	y	200		217.06	232.3
2	100	12	icefree	3.7	0	h	y	n/a	0	0.78	8.92
2	100	12	blocks	3.7	0	h	y	400		11.86	41.16
2	100	12	blocks	3.7	0	h	y	400		68.26	93.92
2	100	12	blocks	3.7	0	h	y	400		140.8	148.12
2	100	13	blocks	5.6	0	h	y	100		5.16	5.6
2	100	13	blocks	5.6	0	h	y	100		13.1	13.44
2	100	13	blocks	5.6	0	h	y	100		24.52	24.86
2	100	13	icefree	5.6	0	h	y	n/a	0	27.2	46.54
2	100	13	blocks	5.6	0	h	y	200		50.24	50.98
2	100	13	blocks	5.6	0	h	y	200		57.3	57.76
2	100	13	blocks	5.6	0	h	y	200		64.78	65.32
2	100	13	blocks	5.6	0	h	y	400		133.34	141.56
2	100	13	blocks	5.6	0	h	y	400		165.9	171.34
2	100	13	blocks	5.6	0	h	y	400		196.92	206.5
2	100	13	icefree	7.5	0	h	y	n/a	0	1.42	13
2	100	14	icefree	5.6	0	h	y	n/a	0	54.9	66.9
2	100	14	blocks	5.6	0	h	y	100		14.3	14.56
2	100	14	blocks	7.5	0	h	y	100		21.58	21.78
2	100	14	blocks	7.5	0	h	y	100		27.04	27.26
2	100	14	blocks	7.5	0	h	y	200		31.26	31.6
2	100	14	blocks	7.5	0	h	y	200		39.1	39.5
2	100	14	blocks	7.5	0	h	y	200		50.28	51.24
2	100	14	blocks	7.5	0	h	y	400		68.8	69.92
2	100	14	blocks	7.5	0	h	y	400		86.06	88.72
2	100	14	blocks	7.5	0	h	y	400		107.28	111.24
2	100	15	icefree	7.5	0.2	h	y	n/a	0	2.3	4.24
2	100	15	presawn	7.5	0.2	h	y	100		4.42	26.1
2	100	16	icefree	7.5	0.2	h	y	n/a	0	8.76	11.22
2	100	16	presawn	7.5	0.2	h	y	200		14.86	80.26
2	100	17	icefree	7.5	0.2	h	y	n/a	0	5.4	11.6

TABLE 4.1. Continuation

2	100	17	blocks	7.5	0.2	h	y	100		16.06	16.24
2	100	17	blocks	7.5	0.2	h	y	100		20.78	20.94
2	100	17	blocks	7.5	0.2	h	y	200		23.58	24.1
2	100	17	blocks	7.5	0.2	h	y	200		29.9	30.44
2	100	17	blocks	7.5	0.2	h	y	200		35.58	36.24
2	100	17	blocks	7.5	0.2	h	y	400		46.1	48.44
2	100	17	blocks	7.5	0.2	h	y	400		55.48	58.96
2	100	17	blocks	7.5	0.2	h	y	400		64.62	70.08
2	100	18	blocks	7.5	1	h	y	100		18.66	18.84
2	100	18	blocks	7.5	1	h	y	100		20.48	20.66
2	100	18	icefree	7.5	1	h	y	n/a	0	20.86	22.98
2	100	18	blocks	7.5	1	h	y	200		25.52	26
2	100	18	blocks	7.5	1	h	y	200		28.64	29.12
2	100	18	blocks	7.5	1	h	y	200		31.38	31.92
2	100	19	blocks	7.5	1	h	y	400		15.36	16.8
2	100	19	icefree	7.5	1	h	y	n/a	0	17.36	20.32
2	100	19	blocks	7.5	1	h	y	400		21.24	23.5
2	100	19	blocks	7.5	1	h	y	400		26.62	28.94
2	100	20	icefree	3.7	1	h	y	n/a	0	10.22	13.06
2	100	20	blocks	3.7	1	h	y	100		13.38	13.78
2	100	20	blocks	3.7	1	h	y	200		16.22	17.7
2	100	20	blocks	3.7	1	h	y	200		20.16	21.74
2	100	21	blocks	3.7	1	h	y	200		18.06	28.6
2	100	21	icefree	3.7	1	h	y	n/a	0	16.42	17.58
2	100	22	icefree	3.7	1	h	y	n/a	0	11.12	12.14
2	100	22	blocks	3.7	1	h	y	400		12.32	21.74
2	100	23	icefree	7.5	0.2	h	y	n/a	0	9.64	17.26
2	100	23	level ice	7.5	0.2	h	y	20 cm cut		21.2	110.44
2	100	24	icefree	7.5	1	h	y	n/a	0	13.1	13.6
2	100	24	level ice	7.5	1	h	y	20 cm cut		17.08	30.02
2	100	25	icefree	7.5	0.2	h	y	n/a	0	4.08	9
2	100	25	level ice	7.5	0.2	h	y	40 cm cut		12.86	104.42
2	100	26	icefree	7.5	0	h	y	n/a	0	1.3	11.1
2	100	27	icefree	3.7	1	h	y	n/a	0	9.42	10.1
2	100	27	level ice	3.7	1	h	y	20 cm cut		10.34	19.98
2	100	28	blocks	7.5	0	h	y	100		14.12	14.36
2	100	28	blocks	7.5	0	h	y	100		18.48	18.78
2	100	28	blocks	7.5	0	h	y	100		28.62	29.02
2	100	28	icefree	7.5	0	h	y	n/a	0	34.6	46.24
2	100	28	blocks	7.5	0	h	y	200		46.78	47.28
2	100	28	blocks	7.5	0	h	y	200		64	64.42
2	100	28	blocks	7.5	0	h	y	200		74.8	75.7
2	100	28	blocks	7.5	0	h	y	400		80.22	82.86
2	100	28	blocks	7.5	0	h	y	400		110.88	113.56
2	100	29	blocks	3.7	0	h	y	100		2.14	2.7
2	100	29	icefree	3.7	0	h	y	n/a	0	30.64	41.54
2	100	29	blocks	3.7	0	h	y	200		42.92	53.28
2	100	29	blocks	3.7	0	h	y	200		69.06	70.92
2	100	29	blocks	3.7	0	h	y	200		81.84	94.52
2	100	29	blocks	3.7	0	h	y	400		126.8	147.28

TABLE 4.1. Continuation

2	100	30	icefree	3.7	0	h	y	n/a	0	4.3	16.18
2	100	30	blocks	3.7	0	h	y	400		17.42	26.94
2	100	30	blocks	3.7	0	h	y	400		45.98	61.22
2	100	31	blocks	3.7	0	l	y	100		0	0.42
2	100	31	blocks	3.7	0	l	y	100		9.24	9.48
2	100	31	blocks	3.7	0	l	y	200		16.14	31.14
2	100	31	blocks	3.7	0	l	y	200		36.06	38.84
2	100	31	blocks	3.7	0	l	y	200		47.18	48.08
2	100	31	icefree	3.7	0	l	y	n/a	0	49.84	66.54
2	100	31	blocks	3.7	0	l	y	400		67.1	75.9
2	100	31	blocks	3.7	0	l	y	400		87.72	91.46
2	100	31	blocks	3.7	0	l	y	400		104.52	117.56
2	100	32	blocks	5.6	0	l	y	100		5.78	7.1
2	100	32	blocks	5.6	0	l	y	100		11.3	11.94
2	100	32	blocks	5.6	0	l	y	100		17.82	18.56
2	100	32	blocks	5.6	0	l	y	200		28.9	46.24
2	100	32	blocks	5.6	0	l	y	200		51.92	88.4
2	100	32	blocks	5.6	0	l	y	200		85.84	88.3
2	100	32	blocks	5.6	0	l	y	400		93.82	118.42
2	100	32	blocks	5.6	0	l	y	400		119.26	121.46
2	100	32	blocks	5.6	0	l	y	400		126.52	128.32
2	100	32	icefree	5.6	0	l	y	n/a	0	133.12	149.08
2	100	32	blocks	5.6	0	l	y	400		155.02	169.82
2	100	33	blocks	7.5	0	l	y	100		10.88	11.4
2	100	33	icefree	7.5	0	l	y	n/a	0	12.12	13.86
2	100	33	blocks	7.5	0	l	y	100		17.24	18.56
2	100	33	blocks	7.5	0	l	y	100		20.38	20.84
2	100	34	blocks	7.5	1	l	y	200		15.94	16.82
2	100	34	icefree	7.5	1	l	y	n/a	0	17.24	20.54
2	100	34	blocks	7.5	1	l	y	200		21.38	22.02
2	100	34	blocks	7.5	1	l	y	400		24.96	27.48
2	100	35	icefree	7.5	0.2	l	y	n/a	0	2.66	12.64
2	100	35	level ice	7.5	0.2	l	y	20 cm	cut?	18.84	99.84
2	100	36	icefree	7.5	1	l	y	n/a	0	4.1	4.9
2	100	36	level ice	7.5	1	l	y	20 cm	cut?	4.68	18.68
2	100	37	icefree	5.6	1	l	y	n/a	0	4.4	4.9
2	100	37	level ice	5.6	1	l	y	20 cm	cut?	4.98	19.18
2	100	38	icefree	5.6	0	l	y	n/a	0	9.86	22.32
2	100	39	icefree	7.5	0	l	y	n/a	0	0.3	14.9
2	100	40	icefree	3.7	0	l	y	n/a	0	1.6	27.8
2	100	41	blockage	3.7	0	l	y	30 %	0	2	27
2	100	42	blockage	5.6	0	l	y	30 %	0	2.4	33.7
2	100	43	blockage	7.5	0	l	y	30 %	0	1.1	17
2	100	44	blockage	7.5	0	l	y	10 %	0	3.8	29.9
3	100	1	icefree	7.5	0	h	n	n/a	0	0.5	22.3
3	100	2	icefree	5.6	0	h	n	n/a	0	2.8	35.7
3	100	3	icefree	3.7	0	h	n	n/a	0	1	16.2
3	100	4	icefree	7.5	0	h	n	n/a	0	49.2	80.5

TABLE 4.1. Continuation

3	100	4	blocks	7.5	0	h	n	100		skip	
3	100	4	blocks	7.5	0	h	n	100		skip	
3	100	4	blocks	7.5	0	h	n	100		skip	
3	100	4	blocks	7.5	0	h	n	200		26.02	26.36
3	100	4	blocks	7.5	0	h	n	200		36.96	37.26
3	100	4	blocks	7.5	0	h	n	200		90.4	90.68
3	100	4	blocks	7.5	0	h	n	400		128.22	128.8
3	100	4	blocks	7.5	0	h	n	400		151.6	152.04
3	100	4	blocks	7.5	0	h	n	400		159.44	160.08
3	100	5	icefree	5.6	0	h	n	n/a	0	39.2	63.5
3	100	5	blocks	5.6	0	h	n	100		9.26	9.6
3	100	5	blocks	5.6	0	h	n	100		35.06	35.26
3	100	5	blocks	5.6	0	h	n	100		67.22	67.58
3	100	5	blocks	5.6	0	h	n	200		83.24	83.6
3	100	5	blocks	5.6	0	h	n	200		96.12	96.46
3	100	5	blocks	5.6	0	h	n	200		107.14	107.46
3	100	5	blocks	5.6	0	h	n	400		132.3	132.9
3	100	5	blocks	5.6	0	h	n	400		158.88	159.54
3	100	5	blocks	5.6	0	h	n	400		185.24	185.88
3	100	6	blocks	3.7	0	h	n	100		27.08	29.04
3	100	6	blocks	3.7	0	h	n	100		38.66	39.38
3	100	6	blocks	3.7	0	h	n	100		51.56	52.92
3	100	6	blocks	3.7	0	h	n	200		71.46	72.04
3	100	6	blocks	3.7	0	h	n	200		84	84.66
3	100	6	blocks	3.7	0	h	n	200		103.06	103.54
3	100	6	icefree	3.7	0	h	n	n/a	0	108.32	129.24
3	100	6	blocks	3.7	0	h	n	400		133.28	134.34
3	100	6	blocks	3.7	0	h	n	400		163.18	163.9
3	100	6	blocks	3.7	0	h	n	400		188.12	189.2
3	100	7	level ice	7.5	0.2	h	n	40 cm cut		17.98	108.38
3	100	7	icefree	7.5	0.2	h	n	n/a	0	9.78	15.78
3	100	8	icefree	7.5	0.2	h	n	n/a	0	4.78	12.98
3	100	8	level ice	7.5	0.2	h	n	20 cm cut		15.1	100.2
3	100	9	icefree	5.6	0.2	h	n	n/a	0	12.52	18.26
3	100	9	level ice	5.6	0.2	h	n	20 cm cut		20.14	106.76
3	100	10	icefree	3.7	0.2	h	n	n/a	0	10.98	13.92
3	100	10	level ice	3.7	0.2	h	n	20 cm cut		14.62	103.94
3	100	11	icefree	3.7	0.2	h	n	n/a	0	8.86	9.44
3	100	11	level ice	3.7	0.2	h	n	20 cm cut		9.84	25.82
3	100	12	icefree	7.5	1	h	n	n/a	0	9.92	10.36
3	100	12	level ice	7.5	1	h	n	20 cm cut		10.72	26.08
3	100	13	icefree	7.5	0.2	h	n	n/a	0	19.2	21.6
3	100	13	blocks	7.5	0.2	h	n	100		12.06	12.3
3	100	13	blocks	7.5	0.2	h	n	100		13.22	13.5
3	100	13	blocks	7.5	0.2	h	n	100		16.28	16.52
3	100	13	blocks	7.5	0.2	h	n	200		18.58	18.84
3	100	13	blocks	7.5	0.2	h	n	200		21.96	22.18
3	100	13	blocks	7.5	0.2	h	n	200		25.18	25.48
3	100	13	blocks	7.5	0.2	h	n	400		26.98	27.32
3	100	13	blocks	7.5	0.2	h	n	400		29.1	29.52

TABLE 4.1. Continuation

3	100	13	blocks	7.5	0.2	h	n	400		32.08	32.42
3	100	14	blocks	7.5	1	h	n	100		6.54	6.78
3	100	14	icefree	7.5	1	h	n	n/a	0	8.8	10.1
3	100	14	blocks	7.5	1	h	n	100		7.56	7.74
3	100	14	blocks	7.5	1	h	n	100		8.52	8.72
3	100	14	blocks	7.5	1	h	n	200		10.16	10.5
3	100	14	blocks	7.5	1	h	n	200		11.58	11.88
3	100	14	blocks	7.5	1	h	n	200		12.52	12.9
3	100	14	blocks	7.5	1	h	n	400		13.62	14.16
3	100	14	blocks	7.5	1	h	n	400		15.58	15.96
3	100	14	blocks	7.5	1	h	n	400		16.9	17.56
3	100	15	blocks	3.7	0.2	h	n	(?)			
3	100	16	icefree	3.7	0	h	n	n/a	0	74.2	188.1
3	100	16	blocks	3.7	0	h	n	100		11.1	12.18
3	100	16	blocks	3.7	0	h	n	100		19.12	20.26
3	100	16	blocks	3.7	0	h	n	100		26.3	26.8
3	100	16	blocks	3.7	0	h	n	200		38.66	39.24
3	100	16	blocks	3.7	0	h	n	200		48.18	48.7
3	100	16	blocks	3.7	0	h	n	200		69.44	69.94
3	100	16	blocks	3.7	0	h	n	400		120.78	121.86
3	100	16	blocks	3.7	0	h	n	400		137.1	138.02
3	100	16	blocks	3.7	0	h	n	400		183.08	184.04
3	100	17	icefree	7.5	0	h	n	n/a	0	88.5	114.8
3	100	17	blocks	7.5	0	h	n	100		14.66	14.92
3	100	17	blocks	7.5	0	h	n	100		21.36	21.58
3	100	17	blocks	7.5	0	h	n	100		28.72	28.92
3	100	17	blocks	7.5	0	h	n	200		38.5	38.86
3	100	17	blocks	7.5	0	h	n	200		45.16	45.44
3	100	17	blocks	7.5	0	h	n	200		67.44	67.76
3	100	17	blocks	7.5	0	h	n	400		85.4	85.98
3	100	17	blocks	7.5	0	h	n	400		118.56	119.14
3	100	17	blocks	7.5	0	h	n	400		131.24	131.72
3	100	18	icefree	3.7	1	h	n	n/a	0	10.46	23.8
3	100	18	icefree	3.7	0.2	h	n	n/a	0	38	64.46
3	100	19	icefree	5.6	1	h	n	n/a	0	10.16	24.38
3	100	19	icefree	5.6	0.2	h	n	n/a	0	34.78	64.24
3	100	20	icefree	7.5	1	h	n	n/a	0	15.32	31.28
3	100	20	icefree	7.5	0.2	h	n	n/a	0	missing	
3	100	21	icefree	7.5	0.2	h	n	n/a	0	6.94	37.62
3	100	22	aircal	0	0	h	n	n/a	0		
3	100	23	watercal	0	0	h	n	n/a	0		
3	100	24	blocks	7.5	0	l	n	100		16.2	16.84
3	100	24	blocks	7.5	0	l	n	100		32.22	32.74
3	100	24	blocks	7.5	0	l	n	100		46.66	47.12
3	100	24	blocks	7.5	0	l	n	200		60.68	61.1
3	100	24	blocks	7.5	0	l	n	200		75.3	75.78
3	100	24	blocks	7.5	0	l	n	200		96.38	96.76
3	100	24	blocks	7.5	0	l	n	400		120.44	121.12
3	100	24	blocks	7.5	0	l	n	400		150.48	151.32
3	100	24	blocks	7.5	0	l	n	400		161.58	162.4

TABLE 4.1. Continuation

3	100	24	icefree	7.5	0	1	n	n/a	0	101.08	119.24
3	100	25	blocks	3.7	0	1	n	100		14.78	15.6
3	100	25	blocks	3.7	0	1	n	100		34.4	38.7
3	100	25	blocks	3.7	0	1	n	100		52.2	53.7
3	100	25	blocks	3.7	0	1	n	200		61.32	64.08
3	100	25	blocks	3.7	0	1	n	200		80.18	81.08
3	100	25	blocks	3.7	0	1	n	200		94.08	94.84
3	100	25	blocks	3.7	0	1	n	400		165.12	166.56
3	100	25	blocks	3.7	0	1	n	400		175.08	176.36
3	100	25	blocks	3.7	0	1	n	400		194.9	199.78
3	100	25	icefree	3.7	0	1	n	n/a	0	143.86	162.54
3	100	26	blocks	7.5	1	1	n	100		12.32	12.74
3	100	26	blocks	7.5	1	1	n	100		13.6	13.84
3	100	26	blocks	7.5	1	1	n	100		14.74	15.04
3	100	26	blocks	7.5	1	1	n	200		17.22	17.5
3	100	26	blocks	7.5	1	1	n	200		18.96	19.44
3	100	26	blocks	7.5	1	1	n	200		20.46	20.84
3	100	26	blocks	7.5	1	1	n	400		21.72	22.18
3	100	26	blocks	7.5	1	1	n	400		23.84	24.24
3	100	26	blocks	7.5	1	1	n	400		25.7	26.52
3	100	26	icefree	7.5	1	1	n	n/a	0	15.16	17.1
3	100	27	icefree	7.5	0.2	1	n	n/a	0	3.98	14.42
3	100	27	level ice	7.5	0.2	1	n	20 cm cut		22.66	158.38
3	100	28	icefree	7.5	1	1	n	n/a	0	6.62	9.36
3	100	28	level ice	7.5	1	1	n	20 cm cut		10.54	29.36
3	100	29	icefree	3.7	1	1	n	n/a	0	11.46	13.58
3	100	29	level ice	3.7	1	1	n	20 cm cut		14.06	30.76
3	100	30	icefree	3.7	1	1	n	n/a	0	13.82	22.7
3	100	30	icefree	3.7	0.2	1	n	n/a	0	33.6	59.02
3	100	31	icefree	5.6	1	1	n	n/a	0	9.08	16.58
3	100	32	icefree	5.6	0.2	1	n	n/a	0	5.96	41.78
3	100	33	icefree	7.5	1	1	n	n/a	0	6.66	14.98
3	100	33	icefree	7.5	0.2	1	n	n/a	0	26.48	48.98
3	200	34	icefree	7.5	0	1	n	n/a	0	55.8	75.7
3	200	34	blocks	7.5	0	1	n	200		31.3	33.06
3	200	34	blocks	7.5	0	1	n	200		50.66	52.1
3	200	34	blocks	7.5	0	1	n	200		78.76	79.5
3	200	34	blocks	7.5	0	1	n	200		105.4	106.54

4	50	1	icefree	3.7	0	h	y	n/a	0	0.7	42
4	50	2	icefree	5.6	0	h	y	n/a	0	1.3	18.9
4	50	3	icefree	7.5	0	h	y	n/a	0	1.3	21
4	50	4	blocks	7.5	0	h	y	100		9.28	9.42
4	50	4	blocks	7.5	0	h	y	100		20.38	20.56
4	50	4	blocks	7.5	0	h	y	100		28.54	28.74
4	50	4	blocks	7.5	0	h	y	200		38.22	38.5
4	50	4	blocks	7.5	0	h	y	200		44.366	44.7
4	50	4	blocks	7.5	0	h	y	200		51.6	51.92
4	50	4	blocks	7.5	0	h	y	400		68.08	70.28

TABLE 4.1. Continuation

4	50	4	blocks	7.5	0	h	y	400		80.96	96.66
4	50	4	blocks	7.5	0	h	y	400		123	124.56
4	50	4	icefree	7.5	0	h	y	n/a	0	53.86	65.76
4	50	5	icefree	5.6	0	h	y	n/a	0	6	39.6
4	50	5	blocks	5.6	0	h	y	100		44.96	45.16
4	50	5	blocks	5.6	0	h	y	100		54.08	54.42
4	50	5	blocks	5.6	0	h	y	100		64.42	64.62
4	50	5	blocks	5.6	0	h	y	200		83.6	84.18
4	50	5	blocks	5.6	0	h	y	200		95.76	96.26
4	50	5	blocks	5.6	0	h	y	200		107.14	107.68
4	50	5	blocks	5.6	0	h	y	400		132.64	135.06
4	50	5	blocks	5.6	0	h	y	400		151.94	154.42
4	50	5	blocks	5.6	0	h	y	400		171.5	183.88
4	50	6	blocks	3.7	0	h	y	100		19.08	19.5
4	50	6	blocks	3.7	0	h	y	100		31.18	31.54
4	50	6	blocks	3.7	0	h	y	100		42.38	42.78
4	50	6	blocks	3.7	0	h	y	200		57.02	58.28
4	50	6	blocks	3.7	0	h	y	200		67.06	68.26
4	50	6	blocks	3.7	0	h	y	200		76.14	77.22
4	50	6	blocks	3.7	0	h	y	400		96.42	102.2
4	50	6	blocks	3.7	0	h	y	400		118.96	126.7
4	50	6	blocks	3.7	0	h	y	400		145.2	153.18
4	50	6	icefree	3.7	0	h	y	n/a	0	79.1	95.48
4	50	7	icefree	3.7	0	h	y	n/a	0	6.36	17.54
4	50	7	level ice	7.5	0.2	h	y	40 cm cut		21.56	149.96
4	50	8	icefree	7.5	0.2	h	y	n/a	0	10.22	17.9
4	50	8	level ice	7.5	0.2	h	y	20 cm cut		21.2	140.44
4	50	9	icefree	5.6	0.2	h	y	n/a	0	5.64	12.22
4	50	9	level ice	5.6	0.2	h	y	20 cm cut		12.96	133.28
4	50	10	icefree	3.7	0.2	h	y	n/a	0	8.74	16.26
4	50	10	level ice	3.7	0.2	h	y	20 cm cut		18.08	138.42
4	50	11	icefree	7.5	1	h	y	n/a	0	25.36	25.9
4	50	11	level ice	7.5	1	h	y	20 cm cut		26.88	49.86
4	50	12	icefree	7.5	1	h	y	n/a	0	4.16	4.64
4	50	12	level ice	7.5	1	h	y	40 cm cut		5.2	28.2
4	50	13	icefree	7.5	1	h	y	n/a	0	0.36	0.76
4	50	13	level ice	7.5	1	h	y	40 cm cut		1.02	25.52
4	50	14	icefree	7.5	1	h	y	n/a	0	9.08	10.1
4	50	14	level ice	7.5	1	h	y	20 cm cut		10.76	32.74
4	50	15	icefree	3.7	1	h	y	n/a	0	9.88	10.62
4	50	15	level ice	3.7	1	h	y	20 cm cut		11.32	34.5
4	50	16	blocks	7.5	0.2	h	y	100		6.22	6.36
4	50	16	blocks	7.5	0.2	h	y	100		14.3	14.56
4	50	16	blocks	7.5	0.2	h	y	100		20.24	20.4
4	50	16	blocks	7.5	0.2	h	y	200		85	85.36
4	50	16	blocks	7.5	0.2	h	y	200		103.08	103.42
4	50	16	blocks	7.5	0.2	h	y	400		111.86	112.4
4	50	16	icefree	7.5	0.2	h	y	n/a	0	29.86	43.36
4	50	17	blocks	7.5	0.2	h	y	400		11.22	12.96
4	50	17	blocks	7.5	0.2	h	y	400		16.96	18.04

TABLE 4.1. Continuation

4	50	17	icefree	7.5	0.2	h	y	n/a	0	6.24	9.2
4	50	18	blocks	3.7	1	h	y	100		6.56	7.22
4	50	18	blocks	3.7	1	h	y	100		8.92	9.26
4	50	18	blocks	3.7	1	h	y	100		10.7	11.1
4	50	18	icefree	3.7	1	h	y	n/a	0	11.56	14.02
4	50	18	blocks	3.7	1	h	y	200		14.4	15.1
4	50	18	blocks	3.7	1	h	y	200		17.22	17.7
4	50	18	blocks	3.7	1	h	y	400		23.08	23.74
4	50	18	blocks	3.7	1	h	y	400		25.78	26.74
4	50	18	blocks	3.7	1	h	y	400		27.36	28.16
4	50	19	blocks	7.5	1	h	y	100		10.52	10.72
4	50	19	blocks	7.5	1	h	y	100		11.72	11.92
4	50	19	blocks	7.5	1	h	y	200		15.64	15.98
4	50	19	blocks	7.5	1	h	y	200		18.82	19.14
4	50	19	blocks	7.5	1	h	y	400		20.16	20.48
4	50	19	blocks	7.5	1	h	y	400		21.64	22.1
4	50	19	blocks	7.5	1	h	y	400		23.44	25.38
4	50	19	icefree	7.5	1	h	y	n/a	0	16.1	18.5
4	50	20	blocks	7.5	0	h	y	100		12.68	12.84
4	50	20	blocks	7.5	0	h	y	100		18.34	18.48
4	50	20	blocks	7.5	0	h	y	100		25.02	25.18
4	50	20	blocks	7.5	0	h	y	200		36.54	36.78
4	50	20	blocks	7.5	0	h	y	200		44.78	45.08
4	50	20	blocks	7.5	0	h	y	200		54.46	54.82
4	50	20	blocks	7.5	0	h	y	400		71.96	73.58
4	50	20	blocks	7.5	0	h	y	400		93.34	94.2
4	50	20	blocks	7.5	0	h	y	400		117.96	118.76
4	50	20	icefree	7.5	0	h	y	n/a	0	95.26	107.9
4	50	21	blocks	7.5	0	l	y	100		8.32	8.52
4	50	21	blocks	7.5	0	l	y	100		14.8	15.04
4	50	21	blocks	7.5	0	l	y	100		27.14	27.42
4	50	21	blocks	7.5	0	l	y	200		33.18	33.7
4	50	21	blocks	7.5	0	l	y	200		43.8	44.3
4	50	21	blocks	7.5	0	l	y	200		52.76	53.2
4	50	21	blocks	7.5	0	l	y	400		73.94	77.1
4	50	21	blocks	7.5	0	l	y	400		102.78	103.92
4	50	21	blocks	7.5	0	l	y	400		117.46	122.2
4	50	21	icefree	7.5	0	l	y	n/a	0	16.06	25.98
4	50	22	blocks	7.5	1	l	y	100		7.4	7.6
4	50	22	blocks	7.5	1	l	y	100		8.22	8.52
4	50	22	blocks	7.5	1	l	y	100		8.86	9.14
4	50	22	blocks	7.5	1	l	y	200		11.04	11.38
4	50	22	blocks	7.5	1	l	y	200		13.38	13.7
4	50	22	blocks	7.5	1	l	y	200		15.34	15.78
4	50	22	blocks	7.5	1	l	y	400		17.46	18.06
4	50	22	blocks	7.5	1	l	y	400		19	19.4
4	50	22	icefree	7.5	1	l	y	n/a	0	15.9	16.76
4	50	23	icefree	7.5	0.2	l	y	n/a	0	6.1	15.32
4	50	23	level ice	7.5	0.2	l	y	40 cm cut?		19.5	185
4	50	24	icefree	7.5	0.2	l	y	n/a	0	6.54	15.76

TABLE 4.1. Continuation

4	50	24	level ice	7.5	0.2	l	y	20 cm cut		24.12	63.02
4	50	24	level ice	7.5	0.2	l	y	20 cm cut		72.92	194.68
4	50	25	icefree	7.5	1	l	y	n/a	0	3.46	4.52
4	50	25	level ice	7.5	1	l	y	20 cm cut		5.18	37.04
4	50	26	icefree	3.7	1	l	y	n/a	0	4.2	5.44
4	50	26	level ice	3.7	1	l	y	20 cm cut		5.96	39.14
4	50	27	icefree	7.5	1	l	y	n/a	0	4.14	4.9
4	50	27	level ice	7.5	1	l	y	40 cm cut		4.74	37.38
5	50	1	icefree	7.5	0	h	n	n/a	0	90.7	104.8
5	50	1	blocks	7.5	0	h	n	100		11.36	11.5
5	50	1	blocks	7.5	0	h	n	100		29.8	29.96
5	50	1	blocks	7.5	0	h	n	100		40.06	40.3
5	50	1	blocks	7.5	0	h	n	200		49.06	49.8
5	50	1	blocks	7.5	0	h	n	200		62.88	64.04
5	50	1	blocks	7.5	0	h	n	200		72.34	72.78
5	50	1	blocks	7.5	0	h	n	400		87.96	88.44
5	50	1	blocks	7.5	0	h	n	400		121.8	123.14
5	50	1	blocks	7.5	0	h	n	400		50.68	62.32
5	50	2	blocks	5.6	0	h	n	100		6.04	6.36
5	50	2	blocks	5.6	0	h	n	100		12.74	13.1
5	50	2	blocks	5.6	0	h	n	100		22.78	23.06
5	50	2	blocks	5.6	0	h	n	200		32.3	32.84
5	50	2	blocks	5.6	0	h	n	200		43.08	43.72
5	50	2	blocks	5.6	0	h	n	200		50.72	51.34
5	50	2	blocks	5.6	0	h	n	400		68.86	69.34
5	50	2	blocks	5.6	0	h	n	400		89.02	89.44
5	50	2	blocks	5.6	0	h	n	400		108.04	108.54
5	50	2	icefree	5.6	0	h	n	n/a	0	71.54	87.92
5	50	3	blocks	3.7	0	h	n	100		15.28	16.02
5	50	3	blocks	3.7	0	h	n	100		23.14	23.82
5	50	3	blocks	3.7	0	h	n	100		39.3	40.34
5	50	3	blocks	3.7	0	h	n	200		52.98	53.98
5	50	3	blocks	3.7	0	h	n	200		65.1	66.14
5	50	3	blocks	3.7	0	h	n	200		80.82	81.72
5	50	3	blocks	3.7	0	h	n	400		108.8	109.72
5	50	3	blocks	3.7	0	h	n	400		130.9	132
5	50	3	blocks	3.7	0	h	n	400		146.18	148.62
5	50	3	icefree	3.7	0	h	n	n/a	0	84	106.46
5	50	4	icefree	7.5	0.2	h	n	n/a	0	8.38	19.56
5	50	4	level ice	7.5	0.2	h	n	60 cm cut		23.58	153.8
5	50	5	icefree	7.5	0.2	h	n	n/a	0	8.02	14.78
5	50	5	level ice	7.5	0.2	h	n	20 cm cut		19.56	80.36
5	50	6	icefree	7.5	0.2	h	n	n/a	0	19.3	24.58
5	50	6	level ice	7.5	0.2	h	n	40 cm cut		26.64	121.28
5	50	7	icefree	5.6	0.2	h	n	n/a	0	7.1	13.88
5	50	7	level ice	5.6	0.2	h	n	20 cm cut		15.34	153.98
5	50	8	icefree	7.5	1	h	n	n/a	0	9.12	10.42
5	50	8	level ice	7.5	1	h	n	20 cm cut		10.82	36.8

TABLE 4.1. Continuation

5	50	9	icefree	5.6	1	h	n	n/a	0	33.82	35
5	50	9	level ice	5.6	1	h	n	20 cm cut		35.66	59.98
5	50	10	icefree	3.7	1	h	n	n/a	0	13.74	14.46
5	50	10	level ice	3.7	1	h	n	20 cm cut		14.94	40.48
5	50	11	blocks	7.5	0.2	h	n	100		20.4	20.56
5	50	11	blocks	7.5	0.2	h	n	100		31.2	31.34
5	50	11	blocks	7.5	0.2	h	n	100		31.36	31.52
5	50	11	blocks	7.5	0.2	h	n	200		38.62	38.94
5	50	11	blocks	7.5	0.2	h	n	200		45.34	45.7
5	50	11	blocks	7.5	0.2	h	n	200		52.82	53.18
5	50	11	blocks	7.5	0.2	h	n	400		60.76	61.28
5	50	11	blocks	7.5	0.2	h	n	400		67.9	68.34
5	50	11	blocks	7.5	0.2	h	n	400		77.52	78.3
5	50	11	icefree	7.5	0.2	h	n	n/a	0	10.5	18.54
5	50	12	blocks	7.5	1	h	n	100		6.88	7.2
5	50	12	blocks	7.5	1	h	n	100		8.5	8.76
5	50	12	blocks	7.5	1	h	n	100		10.18	10.46
5	50	12	blocks	7.5	1	h	n	200		12.4	12.7
5	50	12	blocks	7.5	1	h	n	200		15	15.4
5	50	12	blocks	7.5	1	h	n	200		17.24	17.48
5	50	12	blocks	7.5	1	h	n	400		18.32	18.68
5	50	12	blocks	7.5	1	h	n	400		20.12	21.08
5	50	12	blocks	7.5	1	h	n	400		21.9	22.3
5	50	12	icefree	7.5	1	h	n	n/a	0	13	14.66
5	50	13	blocks	3.7	1	h	n	100		8.2	8.68
5	50	13	blocks	3.7	1	h	n	100		10.26	10.62
5	50	13	blocks	3.7	1	h	n	100		11.42	11.9
5	50	13	blocks	3.7	1	h	n	200		13.38	13.64
5	50	13	blocks	3.7	1	h	n	200		15.4	15.84
5	50	13	blocks	3.7	1	h	n	200		17.66	18.06
5	50	13	blocks	3.7	1	h	n	400		18.82	19.72
5	50	13	blocks	3.7	1	h	n	400		20.86	21.54
5	50	13	blocks	3.7	1	h	n	400		22.8	23.5
5	50	13	icefree	3.7	1	h	n	n/a	0	13.74	15.28
5	50	14	blocks	7.5	0	l	n	100		5.1	5.28
5	50	14	blocks	7.5	0	l	n	100		12.56	12.82
5	50	14	blocks	7.5	0	l	n	100		24.5	25.08
5	50	14	blocks	7.5	0	l	n	200		35.84	36.48
5	50	14	blocks	7.5	0	l	n	200		48.36	48.74
5	50	14	blocks	7.5	0	l	n	200		64.3	64.68
5	50	14	blocks	7.5	0	l	n	400		99.1	99.58
5	50	14	blocks	7.5	0	l	n	400		120.16	120.74
5	50	14	icefree	7.5	0	l	n	n/a	0	105.1	117.34
5	50	15	blocks	7.5	1	l	n	100		10.14	10.48
5	50	15	blocks	7.5	1	l	n	100		11.3	11.6
5	50	15	blocks	7.5	1	l	n	100		12.6	12.82
5	50	15	blocks	7.5	1	l	n	200		14.46	14.68
5	50	15	blocks	7.5	1	l	n	200		15.36	16.1
5	50	15	blocks	7.5	1	l	n	200		16.16	16.44
5	50	15	blocks	7.5	1	l	n	400		17.58	18.38

TABLE 4.1. Continuation

5	50	15	blocks	7.5	1	1	n	400		19.46	20.38
5	50	15	blocks	7.5	1	1	n	400		20.96	21.92
5	50	15	icefree	7.5	1	1	n	n/a	0	12.92	14.34
5	50	16	icefree	7.5	1	1	n	n/a	0	10.32	12
5	50	16	level ice	7.5	1	1	n	20 cm cut		12.28	42.84
5	50	17	icefree	7.5	0.2	1	n	n/a	0	8.08	19.28
5	50	17	level ice	7.5	0.2	1	n	20 cm cut		22.36	179.94
5	50	18	icefree	3.7	1	1	n	n/a	0	6.02	7.72
5	50	18	level ice	3.7	1	1	n	20 cm cut		8.48	37.78
5	160	19	blocks	7.5	0	1	n	200		32.76	33.56
5	160	19	blocks	7.5	0	1	n	200		46.94	47.68
5	160	19	blocks	7.5	0	1	n	200		56.28	56.7
5	160	19	blocks	7.5	0	1	n	400		104.66	106.26
5	160	19	icefree	7.5	0	1	n	n/a	0	66.78	97.9
5	190	21	icefree	7.5	0	1	n	n/a	0	58.2	92.3
5	190	21	blocks	7.5	0	1	n	200		24.78	25.36
5	190	21	blocks	7.5	0	1	n	200		50	50.52
5	190	21	blocks	7.5	0	1	n	400		101.1	104.82
5	190	22	blocks	7.5	0	1	n	400		11.12	20.94
5	190	22	icefree	7.5	0	1	n	n/a	0	3.18	10.16
5	190	23	blocks	7.5	0	1	n	400		13.68	17.08
5	190	23	icefree	7.5	0	1	n	n/a	0	6.82	13.04
5	50	24	icefree	3.7	0	1	n	n/a	0	1.5	37.3
5	50	25	icefree	5.6	0	1	n	n/a	0	0.8	20.9
5	50	26	icefree	7.5	0	1	n	n/a	0	0.5	17.7
5	50	27	icefree	7.5	0	1	n	n/a	0	1.04	6.66
5	50	27	premilled	7.5	0	1	n	50% 1/2 di	0	22.26	31.04
5	50	28	icefree	7.5	0	1	n	n/a	0	31.58	35.38
5	50	28	premilled	7.5	0	1	n	50% 1/2 di	0	18.62	23.94
5	50	29	premilled	7.5	0	1	n	30 %	0	17.5	21.66
5	50	29	icefree	7.5	0	1	n	n/a	0	27.02	37.86
5	50	29	premilled	7.5	0	1	n	30 %	0	47.38	50.82
5	50	30	premilled	7.5	0	1	n	10 %	0	17.1	22.14
5	50	30	icefree	7.5	0	1	n	n/a	0	28	37.84
5	50	30	premilled	7.5	0	1	n	10 %	0	43.42	48.04

Table 5.2.1.1
Hydrodynamic Means
Mean of data Used for the Analysis

		DUCTED SCREW						OPEN SCREW					
		To, mean N			Qo, mean Nm			To, mean N			Qo, mean Nm		
Pitch	rps	0	0.2	1.0	0	0.2	1.0	0	0.2	1.0	0	0.2	1.0
High	7.5	150.68	151.01	131.94	11.32	11.48	10.40	244.93	244.91	201.74	17.35	17.41	14.60
High	5.6	81.96			5.83			137.32			9.49		
High	3.7	34.68		24.91	3.67		2.83	56.05	51.88	32.86	5.60	6.07	2.26
Low	7.5	55.93		30.56	4.05		3.12	123.19		63.20	5.73		3.86
Low	5.6	25.57			2.35								
Low	3.7	5.99			1.45			23.38			2.90		

TABLE 5.2.2.1
PROPELLER - ICE INTERACTION
ICE BLOCK BLOCKAGE
DUCTED SCREW - EFFECT OF BLOCKAGE

DAY	RUNS	ICE THICK (mm)	BLOCK SIZE (mm^2)	PITCH	RPS	V (m/s)	TORQUE (Nm)		BLOCKAGE TYPE	THRUST (N)	
							Bmax-Bmean	Bmean-Omean		Bmax-Bmean	Bmean-Omean
2	13	100	400	H	5.6	0.0	4.03	1.67	4	68	---
2	31	100	400	L	7.5	0.0	2.29	0.59	4	71.6	---
2	12,29,30	100	400	H	3.7	0.0	3.08	1.68	3	50	9
2	32	100	400	L	5.6	0.0	2.58	0.60	4	44	---
2	22	100	400	H	3.7	1.0	3.91	1.63	2 & 3	31.6	5.29
4	4,20	100	400	H	7.5	0.0	3.80	0.60	4	52.4	11.4
4	5	100	400	H	5.6	0.0	1.47	0.67	4	31.8	8.7
2	19	100	400	H	7.5	1.0	----	----	3 & 4	31	---
2	29	100	200	H	3.7	0.0	3.47	1.27	5 & 1	37.5	---
2	11	100	200	H	3.7	0.0	4.00	1.00	1 & 2	44	---
2	31	100	200	L	7.5	0.0	3.33	1.33	1	58.04	---
2	32	100	200	L	5.6	0.0	1.40	0.91	1	35	---
2	21	100	200	H	3.7	1.0	3.03	1.60	1	33	8.3

TABLE 5.2.2.2
PROPELLER - ICE INTERACTION
ICE BLOCK BLOCKAGE
THRUST AND TORQUE BLOCKAGE VALUES AT ZERO STRENGTH
BOLLARD CONDITION

		THRUST (N)			TORQUE (Nm)		
	rps	Bmax - Bmean	Bmean - Omean	Bmax - Omean	Bmax - Bmean	Bmean - Omean	Bmax - Omean
100 mm THICK HIGH PITCH 400 BLOCKS	7.5	114	28	142	5.8	2.65	8.45
	5.6	68	17	85	4.0	1.7	5.73
	3.7	42	9	51	2.7	0.95	3.65
100 mm THICK HIGH PITCH 200 BLOCKS	7.5	93	23	116	4.8	2.2	7.0
	5.6	56	14	70	3.3	1.4	4.7
	3.7	34	7	41	2.2	0.8	3.0
100 mm THICK LOW PITCH 400 BLOCKS	7.5	71	28	99	3.6	1.1	4.7
	5.6	42.5	17	59.5	2.5	0.7	3.2
	3.7	26	9	35	1.7	0.4	2.1
100 mm THICK LOW PITCH 200 BLOCKS	7.5	58	23	81	3.0	0.9	3.9
	5.6	35	14	49	2.0	0.6	2.6
	3.7	21	7	29	1.3	0.3	1.6
50 mm THICK HIGH PITCH 400 BLOCKS	7.5	52	14	66	2.7	1.2	3.9
	5.6	31.5	8.5	40	1.9	0.8	2.7
	3.7	20	4	24	1.25	0.4	1.65
50 mm THICK HIGH PITCH 200 BLOCKS	7.5	43	11	54	2.2	1.0	3.2
	5.6	26	7	33	1.6	0.65	2.25
	3.7	16	3	19	1.0	0.3	1.3
50 mm THICK LOW PITCH 400 BLOCKS	7.5	32	14	46	2.2	0.5	2.7
	5.6	20	8.5	28.5	1.35	0.3	1.65
	3.7	14	4	18	0.9	0.2	1.1
50 mm THICK LOW PITCH 200 BLOCKS	7.5	27	11	38	2.2	0.4	2.6
	5.6	20	7	27	1.35	0.3	1.65
	3.7	14	3	17	0.9	0.2	1.1

TABLE 5.2.2.3
PROPELLER - ICE INTERACTION
ICE BLOCK BLOCKAGE
THRUST AND TORQUE BLOCKAGE VALUES AT ZERO STRENGTH
V = 0.2 M/S

		THRUST (N)			TORQUE (Nm)		
	BLOCKS	Bmax - Bmean	Bmean - Omean	Bmax - Omean	Bmax - Bmean	Bmean - Omean	Bmax - Omean
100 mm THICK HIGH PITCH 7.5 RPS	400	111	27	138	5.7	2.6	8.3
	200	90	22	113	4.7	2.2	6.9
	100	---	---	---	---	---	---
100 mm THICK LOW PITCH 7.5 RPS	400	69	27	96	3.5	1.1	4.6
	200	56	22	79	2.9	0.9	3.8
	100	---	---	---	---	---	---
50 mm THICK HIGH PITCH 7.5 RPS	400	50	4	64	2.6	1.2	3.8
	200	42	11	53	2.2	1.0	3.2
	100	---	---	---	---	---	---

TABLE 5.2.2.4
PROPELLER - ICE INTERACTION
ICE BLOCK BLOCKAGE
THRUST AND TORQUE BLOCKAGE VALUES AT ZERO STRENGTH
V = 1.0 M/S

		THRUST (N)			TORQUE (Nm)		
	rps	Bmax - Bmean	Bmean - Qmean	Bmax - Qmean	Bmax - Bmean	Bmean - Qmean	Bmax - Qmean
100 mm THICK HIGH PITCH 400 BLOCKS	7.5 5.6 3.7	96 --- 35	24 --- 7	119 --- 43	5.3 --- 2.5	2.4 --- 0.9	7.8 --- 3.4
100 mm THICK HIGH PITCH 200 BLOCKS	7.5 5.6 3.7	78 --- 29	19 --- 6	97 --- 34	4.4 --- 2.0	2.0 --- 0.7	6.4 --- 2.8
50 mm THICK HIGH PITCH 400 BLOCKS	7.5 5.6 3.7	44 --- 17	12 --- 3	55 --- 20	2.5 --- 1.2	1.1 --- 0.4	3.6 --- 1.5
50 mm THICK HIGH PITCH 200 BLOCKS	7.5 5.6 3.7	36 --- 13	9 --- 2	45 --- 16	2.0 --- 0.9	0.9 --- 0.3	2.9 --- 1.2
	BLOCKS						
100 mm THICK LOW PITCH 7.5 RPS	400 200 100	60 49 ---	24 19 ---	83 68 ---	3.3 2.8 ---	1.0 0.8 ---	4.3 3.6 ---
50 mm THICK LOW PITCH 7.5 RPS	400 200 100	27 23 ---	12 9 ---	39 32 ---	2.0 2.0 ---	0.5 0.4 ---	2.5 2.4 ---

TABLE 5.2.3.i
OPEN SCREW
THRUST AND TORQUE STRENGTH VALUES FOR PREMILLED HYDRODYNAMIC INTERFERENCE
50 mm DEPTH OF CUT

LOW PITCH						
			THRUST (N)		TORQUE (Nm)	
	RPS	V (m/s)	Tpmax - Tomean	Tpmean - Tomean	Qpmax - Qomean	Qpmean - Qomean
400 BLOCKS	7.5	0	50	14	3.4	0.5
	5.6	0	30	8	2.3	0.3
	3.7	0	18	5	1.5	0.2
200 BLOCKS	7.5	0	50	14	3.4	0.5
	5.6	0	30	8	2.3	0.3
	3.7	0	18	5	1.5	0.2
HIGH PITCH						
400 BLOCKS	7.5	0	71	14	6.12	1.2
	5.6	0	43	8	4.14	0.7
	3.7	0	26	5	2.7	0.5
200 BLOCKS	7.5	0	71	14	6.12	1.2
	5.6	0	43	8	4.14	0.7
	3.7	0	26	5	2.7	0.5

FACTORS FOR	0.2 M/S	1.0 M/S
THRUST	0.97	0.84
TORQUE	0.98	0.92

Table 5.2.4
Hydrodynamic Means
Mean of data Used for the Analysis

		DUCTED SCREW						OPEN SCREW					
		To, mean N			Qo, mean Nm			To, mean N			Qo, mean Nm		
Pitch	rps	0	0.2	1.0	0	0.2	1.0	0	0.2	1.0	0	0.2	1.0
High	7.5	150.68	151.01	131.94	11.32	11.48	10.40	244.93	244.91	201.74	17.35	17.41	14.60
High	5.6	81.96			5.83			137.32			9.49		
High	3.7	34.68		24.91	3.67		2.83	56.05	51.88	32.86	5.60	6.07	2.26
Low	7.5	55.93		30.56	4.05		3.12	123.19		63.20	5.73		3.86
Low	5.6	25.57			2.35								
Low	3.7	5.99			1.45			23.38			2.90		

Table 5.2.4.1
Ducted Screw, Individual Blocks
Direct Ice Load Indices
High Pitch, 0 m/s

					THRUST				TORQUE				
Ice Thickness	Block Size	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	400	7.5	2/14	29.1	147.33	247.18	115.77	0.68	9.78	36.47	13.40	0.65	0.03
100	200	7.5	2/14	28.1	147.33	236.76	104.59	1.39	9.78	30.01	12.99	0.47	0.04
100	400	7.5	2/28	19.3	150.85	236.47	117.78	0.24	11.94	29.64	15.24	0.48	0.03
100	200	7.5	2/28	19.3	150.85	227.16	113.95	1.05	11.94	26.96	15.55	0.42	0.07
50	400	7.5	4/4	59.5	153.26	227.73	140.66	0.59	11.50	31.15	15.05	0.26	0.04
50	200	7.5	4/4	59.5	153.26	233.73	132.58	0.98	11.50	24.09	15.10	0.16	0.04
50	400	7.5	4/20	28.3	151.26	216.38	129.60	1.23	12.06	25.70	13.90	0.34	0.02
50	200	7.5	4/20	28.3	151.26	187.08	132.91	0.39	12.06	24.27	14.66	0.32	0.06
100	400	5.6	2/13	28.7	80.39	201.10	59.16	2.58	4.96	25.72	9.01	0.52	0.08
100	200	5.6	2/13	28.7	80.39	150.38	39.64	1.91	4.96	19.69	8.89	0.35	0.09
50	400	5.6	4/5	57.8	83.52	152.89	65.26	0.97	6.69	23.89	8.39	0.25	0.02
50	200	5.6	4/5	57.8	83.52	128.55	62.96	0.68	6.69	21.16	8.76	0.21	0.02
100	200	3.7	2/11										
100	400	3.7	2/12	29.0									
100	400	3.7	2/29	19.1									
100	200	3.7	2/29	19.1	35.04	65.55	5.20	1.38	3.95	15.93	5.70	0.47	0.05
100	400	3.7	2/30	18.9	30.00	64.10	-25.44	2.52	3.79	19.35	5.64	0.63	0.05
50	400	3.7	4/6	56.1	34.32	80.27	24.25	0.64	3.27	16.63	4.33	0.21	0.01
50	200	3.7	4/6	56.1	34.32	66.15	13.33	0.66	3.27	12.29	4.84	0.14	0.02

Table 5.2.4.2
Ducted Screw Individual Blocks
Direct Ice Load Indices
High Pitch 0.2 m/s

					THRUST				TORQUE				
Ice Thickness	Block Size	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Slope	Qo,mean	Qm,max	Qm,mean	Qmax Slope	Qmean Slope
100	400	7.5	2/17	24.1	151.24	239.37	102.08	1.09	11.13	38.22	15.65	0.78	0.08
100	200	7.5	2/17	24.1	151.24	265.46	115.75	2.48	11.13	43.96	15.57	1.08	0.09
50	400	7.5	4/16	34.8	150.79	181.08	136.35	-0.15	11.83	16.78	12.68	0.033	-0.01
50	200	7.5	4/16	34.8	150.79	173.39	123.85	0.22	11.83	21.26	14.24	0.18	0.04
50	400	7.5	4/17	33.9	150.79	229.73	137.71	1.24	11.83	21.79	13.42	0.18	0.01

Table 5.2.4.3
Ducted Screw Individual Blocks
Direct Ice Load Indices
High Pitch 1.0 m/s

					THRUST				TORQUE				
Ice Thickness	Block Size	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	200	7.5	2/18	23.6	136.07	183.11	[illegible]	1.19	10.22	41.52	14.96	1.05	0.12
100	400	7.5	2/19	23.2	135.08	299.65	[illegible]	4.84	10.46	45.69	14.78	1.18	0.08
50	400	7.5	4/19	29.8	124.68	190.22	114.87	1.05	10.51	21.87	12.49	0.26	0.03
50	200	7.5	4/19	29.8	[illegible]	152.99	113.97	0.10	10.51	20.06	12.29	0.22	0.03
100	200	3.7	2/20	22.8	28.23	73.23	12.75	1.38	2.40	13.84	4.47	0.38	0.06
100	200	3.7	2/21	22.7									
100	400	3.7	2/22	22.6									
50	400	3.7	4/18	31.5	24.91	68.24	9.03	1.34	3.26	16.78	6.14	0.38	0.08
50	200	3.7	4/18	31.5	24.91	41.13	14.24	0.44	3.26	12.23	4.04	0.25	0.02

Table 5.2.4.4
Ducted Screw, Individual Blocks
Direct Ice Load Indices
Low Pitch, 0 s/s

					THRUST				TORQUE				
Ice Thickness	Block Size	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	400	7.5	2/31	17.6	46.86	212.95	31.82	6.26	3.57	26.39	7.18	1.02	0.14
100	200	7.5	2/31	17.6	46.86	100.06	46.24	0.002	3.57	17.37	4.89	0.56	0.02
50	400	7.5	4/21	23.1	64.99	168.59	61.80	3.24	4.52	20.11	6.98	0.56	0.08
50	200	7.5	4/21	23.1	64.99	112.24	46.96	1.66	4.52	13.47	6.33	0.28	0.06
100	400	5.6	2/32	17.4	24.57	124.40	16.68	3.75	2.35	15.66	3.93	0.58	0.05
100	200	5.6	2/32	17.4	24.57	71.91	18.44	1.06	2.35	15.17	4.30	0.59	0.08

Table 5.2.4.5
Ducted Screw, Individual Blocks
Direct Ice Load Indices
Low Pitch, 1.0 m/s

					THRUST				TORQUE				
Ice Thickness	Block Size	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	400	7.5	2/34	16.9	22.36	97.40	28.69	0.52	2.75	17.08	5.23	0.59	0.09
100	200	7.5	2/34	16.9	22.36	121.24	10.43	3.66	2.75	20.77	5.69	0.85	0.13
50	400	7.5	4/22	21.7	38.76	77.59	29.32	1.28	3.49	17.62	7.062	0.54	0.14
50	200	7.5	4/22	21.7	38.76	87.96	33.69	1.44	3.49	12.91	5.49	0.32	0.07

Table 5.2.4.6
Open Screw, Individual Blocks
Direct Ice Load Indices
High Pitch, 0 m/s

					THRUST				TORQUE				
Ice Thickness	Block Size	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	400	7.5	3/4	17.9	234.65	357.26	254.12	2.57	17.26	42.06	27.57	1.04	.51
100	200	7.5	3/4	17.9	234.65	331.59	236.98	2.10	17.26	31.92	18.88	.48	.02
100	400	7.5	3/17	17.0	245.00	428.46	282.68	5.22	18.87	48.84	26.77	1.40	.39
100	200	7.5	3/17	17.0	245.00	354.49	265.11	1.90	18.87	36.41	22.6	.67	.15
50	400	7.5	5/1	63.5	255.14	321.07	231.57	.51	15.92	26.26	17.07	.07	.00
50	200	7.5	5/1	63.5	255.14	291.29	226.03	.13	15.92	30.76	17.13	.14	.00
100	400	5.6	3/5	17.9	133.22	412.96	183.09	10.9	10.46	50.98	18.96	2.03	.44
100	200	5.6	3/5	17.9	133.15	261.06	146.43	4.45	10.46	28.86	14.85	.80	.21
50	400	5.6	5/2	62.7	141.42	208.51	112.47	.97	8.52	22.82	10.84	.16	.03
50	200	5.6	5/2	62.7	141.42	197.55	114.33	.77	8.52	24.57	9.56	.19	.01
100	400	3.7	3/6	17.8	58.07	335.84	77.64	13.3	5.23	37.34	10.44	1.65	.26
100	200	3.7	3/6	17.8	58.07	160.44	58.03	4.57	5.23	22.85	7.31	.84	.09
100	400	3.7	3/16	17.0	53.05	164.56	59.03	4.97	5.96	27.61	9.89	1.11	.20
100	200	3.7	3/16	17.0	53.05	213.95	68.49	7.32	5.96	32.77	9.59	1.42	.18
50	400	3.7	5/3	62.6	57.03	107.58	47.01	.63	2.96	19.04	4.12	.21	.01
50	200	3.7	5/3	62.6	57.03	108.31	46.58	.65	2.96	22.17	3.84	.26	.01

Table 5.2.4.7
Open Screw, Individual Blocks
Direct Ice Load Indices
High Pitch, 0.2 m/s

					THRUST				TORQUE				
Ice Thickness	Block Size	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	400	7.5	3/13	17.3	240.85	386.46	266.04	3.67	18.64	42.26	28.58	1.01	.51
100	200	7.5	3/13	17.3	240.85	375.11	270.51	2.75	18.64	37.38	26.52	.73	.39
50	400	7.5	5/11	47.6	248.97	272.36	205.23	.21	16.18	30.77	17.95	.18	.01
50	200	7.5	5/11	47.6	248.97	301.04	210.28	.71	16.18	25.99	18.03	.08	.01
100	400	3.7	3/15	17.2	51.88	184.59	51.8	6.5	6.07	30.3	10.98	1.25	.26
100	200	3.7	3/15	17.2	51.88	105.69	48.96	2.08	6.07	33.66	12.87	1.45	.37

Table 5.2.4.8
Open Screw, Individual Blocks
Direct Ice Load Indices
High Pitch, 1.0 m/s

					THRUST				TORQUE				
Ice Thickness	Block Size	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	400	7.5	3/14	17.2	197.21	327.87	170.53	5.83	15.69	48.87	24.33	1.57	.43
100	200	7.5	3/14	17.2	197.59	290.27	178.02	3.21	15.74	52.49	18.9	1.78	.11
50	400	7.5	5/12	46.4	206.08	288.24	155.26	1.64	13.48	31.44	18.01	.26	.07
50	200	7.5	5/12	46.4	206.08	233.65	169.43	.16	13.48	29.30	16.66	.21	.04
50	400	3.7	5/13	45.1	32.86	88.65	9.47	1.29	2.26	23.75	6.29	.42	.08
50	200	3.7	5/13	45.1	32.86	105.58	33.47	1.13	2.26	15.42	4.33	.23	.03

Table 5.2.4.9
Open Screw, Individual Blocks
(Including Very Thick Blocks)
Direct Ice Load Indices
Low Pitch, 0 m/s

					THRUST				TORQUE				
Ice Thickness	Block Size	rps	Day/Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	400	7.5	3/24	16.6	112.80	330.95	141.51	9.2	6.31	31.81	13.48	1.33	0.40
100	200	7.5	3/24	16.6	112.80	225.24	119.95	4.17	6.31	24.25	9.85	0.88	0.18
50	400	7.5	5/14	39.3	133.58	155.95	107.71	0.31	5.14	18.63	7.21	0.26	0.04
50	200	7.5	5/14	39.3	133.58	182.97	113.27	0.86	5.14	17.75	8.17	0.23	0.06
100	400	3.7	3/25	16.5	23.38	213.86	28.22	10.5	2.9	29.84	4.72	1.54	0.10
100	200	3.7	3/25	16.5	23.38	116.96	26.67	4.68	2.9	17.32	4.53	0.78	0.09
200	200	7.5	3/34	15.9	132.11	439.14	140.43	16.5	6.57	52.49	14.58	2.67	0.47
190	200	7.5	5/21	29.3	133.95	562.51	123.69	13.7	5.20	69.42	9.44	2.08	0.13
190	400	7.5	5/21	29.3	133.95	321.14	93.55	6.54	5.20	61.58	17.94	1.81	0.42
190	400	7.5	5/22	28.8	134.49	462.82	74.94	12.2	4.99	69.24	17.64	2.11	0.42
190	400	7.5	5/23	28.2	126.19	609.94	91.52	17.11	4.80	69.42	12.46	2.17	0.25

Table 5.2.4.10
Open Screw, Individual Blocks
Direct Ice Load Indices
Low Pitch, 1.0 m/s

					THRUST				TORQUE				
Ice Thickness	Block Size	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	400	7.5	3/26	16.5	49.91	107.60	13.66	3.51	4.34	33.39	17.13	1.55	0.75
100	200	7.5	3/26	16.5	49.91	255.31	29.63	11.5	4.34	27.55	11.11	1.20	0.38
50	400	7.5	5/15	38.0	76.48	169.95	62.02	1.89	3.38	30.02	8.27	0.61	0.12
50	200	7.5	5/15	38.0	76.48	136.07	73.89	0.69	3.38	17.90	4.78	0.29	0.02

Table 5.2.5.1
Ducted Screw, Level Ice
Direct Ice Load Indices
High Pitch, 0.2 m/s

					THRUST				TORQUE				
Ice Thickness	Cut Width	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	20	7.5	2/23	22.3	157.64	276.71	142.09	1.96	11.56	43.22	14.16	1.11	0.02
100	40	7.5	2/25	21.8	164.93	401.89	127.92	7.47	12.46	65.32	17.10	2.04	0.09
50	40	7.5	4/7	53.3	143.89	262.44	125.40	1.63	10.98	32.88	13.22	0.34	0.02
50	20	7.5	4/8	51.3	142.04	219.95	135.95	0.82	10.92	27.88	11.79	0.27	0.00
50	20	5.6	4/9	48.8	74.93	158.53	66.57	1.37	6.25	23.92	7.26	0.32	0.01
50	20	3.7	4/10	47.2	30.20	107.11	20.86	1.50	3.22	19.84	4.31	0.33	0.01

Table 5.2.5.2
Ducted Screw, Level Ice
Direct Ice Load Indices
High Pitch, 1.0 m/s

					THRUST				TORQUE				
Ice Thickness	Cut Width	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	20	7.5	2/24	22.0	144.74	341.44	39.24	10.19	11.22	59.39	21.62	1.90	0.38
50	20	7.5	4/11	45.4	122.14	225.83	83.18	2.35	10.07	34.16	13.42	0.47	0.05
50	40	7.5	4/12	43.7	122.21	218.62	66.71	2.47	10.18	40.56	15.89	0.61	0.11
50	40	7.5	4/13	42.3	120.37	248.97	79.86	2.95	10.24	41.88	16.30	0.66	0.12
50	20	5.6	4/14	40.9	60.64	148.06	27.38	2.42	5.74	23.16	9.40	0.41	0.08
100	20	3.7	2/27	20.1	39.85	98.48	10.63	2.98	2.96	32.48	8.53	1.33	0.24
50	20	3.7	4/15	39.8	17.10	72.98	-5.53	1.65	2.82	21.15	5.84	0.43	0.07

Table 5.2.5.3
Ducted Screw, Level Ice
Direct Ice Load Indices
Low Pitch 0.2 m/s

					THRUST				TORQUE				
Ice Thickness	Cut Width	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	20	7.5	2/35	16.7	42.44	278.81	54.93	9.99	3.40	38.21	7.24	1.86	0.18
50	40	7.5	4/23	20.6	57.44	207.36	51.03	6.08	4.32	24.05	6.84	0.83	0.10
50	20	7.5	4/24	19.8	57.66	123.01	52.94	2.21	4.19	16.02	5.07	0.47	0.02
50	20	7.5	4/24	19.8	57.66	120.61	55.27	1.98	4.19	23.23	4.99	0.83	0.02

Table 5.2.5.4
Ducted Screw, Level Ice
Direct Ice Load Indices
Low Pitch, 1.0 m/s

					THRUST				TORQUE				
Ice Thickness	Cut Width	rps	Day/Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	20	7.5	2/36	16.5	16.08	239.57	7.15	11.11	2.92	38.62	9.87	1.95	0.37
50	20	7.5	4/25	19.0	36.52	143.69	19.18	5.34	3.49	28.17	6.58	1.17	0.14
50	40	7.5	4/27	18.2	36.71	164.50	19.71	6.47	3.84	32.18	8.53	1.42	0.23
100	20	5.6	2/37	16.4	-0.64	177.75	1.39	8.98	1.56	35.21	6.70	1.91	0.28
50	20	3.7	4/26	18.6	-6.52	40.76	-15.67	2.57	1.02	12.37	3.22	0.56	0.10

Table 5.2.5.5
Open Screw, Level Ice
Direct Ice Load Indices
High Pitch, 0.2 m/s

					THRUST				TORQUE				
Ice Thickness	Cut Width	rps	Day/Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	40	7.5	3/7	17.7	239.25	415.76	239.27	6.75	17.56	43.36	19.67	1.11	0.05
100	20	7.5	3/8	17.6	241.93	378.24	239.11	4.67	17.76	38.40	19.05	0.83	0.01
50	60	7.5	5/4	59.3	244.75	382.00	223.71	1.71	15.23	42.13	16.22	0.35	0.01
50	20	7.5	5/5	57.5	247.43	314.00	230.65	0.46	15.51	29.99	15.80	0.15	0.00
50	40	7.5	5/6	56.2	249.40	344.49	229.09	1.04	15.73	39.14	16.44	0.31	0.00
100	20	5.6	3/9	17.6	130.87	265.71	129.12	5.77	10.55	32.82	11.79	1.03	0.03
50	20	5.6	5/7	54.8	135.80	206.88	122.15	0.91	8.44	24.50	8.81	0.22	0.00
100	20	3.7	3/10	17.5	52.08	162.72	51.10	5.17	5.24	24.60	6.28	0.95	0.03

Table 5.2.5.6
Open Screw, Level Ice
Direct Ice Load Indices
High Pitch, 1.0 m/s

					THRUST				TORQUE				
Ice Thickness	Cut Width	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	20	7.5	3/12	17.4	193.36	365.14	142.45	6.60	15.20	49.71	23.15	1.63	0.39
50	20	7.5	5/8	53.6	192.78	274.24	156.67	1.13	12.36	51.59	15.50	0.62	0.04
50	20	5.6	5/9	52.8	91.31	201.68	64.58	1.93	5.81	32.49	9.47	0.43	0.06
100	20	3.7	3/11	17.5	27.22	112.09	-27.31	3.65	3.97	35.97	10.48	1.67	0.34
50	20	3.7	5/10	52.1	27.68	109.64	7.83	1.55	1.60	21.72	4.75	0.33	0.05

Table 5.2.5.7
Open Screw, Level Ice
Direct Ice Load Indices
Low Pitch 0.2 m/s

					THRUST				TORQUE				
Ice Thickness	Cut Width	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	20	7.5	3/27	16.3	108.55	259.68	103.49	7.37	6.21	28.86	7.63	1.18	0.06
50	20	7.5	5/17	36.4	123.19	210.66	108.01	1.83	4.82	21.79	5.63	0.37	0.01

Table 5.2.5.8
Open Screw, Level Ice
Direct Ice Load Indices
Low Pitch 1.0 m/s

					THRUST				TORQUE				
Ice Thickness	Cut Width	rps	Day/ Run	Ice Strength	To,mean	Tm,max	Tm,mean	Tmax Index	Qo,mean	Qm,max	Qm,mean	Qmax Index	Qmean Index
100	20	7.5	3/28	16.3	59.70	277.65	-5.62	15.26	4.66	40.82	13.54	2.02	0.51
50	20	7.5	5/16	37.1	76.19	193.25	39.87	3.16	3.45	43.73	7.63	0.99	0.10
100	20	3.7	3/29	16.2	-1.16	138.47	-44.36	10.48	1.61	39.52	7.55	2.13	0.35
50	20	3.7	5/18	35.6	0.70	76.37	-18.15	2.29	-0.07	24.99	3.20	0.66	0.09

TABLE 6.6.1
SUMMARY AND COMPARISONS OF INDIVIDUAL BLOCKS AND LEVEL ICE TESTS

PARAMETER	INDIVIDUAL BLOCKS		LEVEL ICE	
	DUCTED	OPEN	DUCTED	OPEN
Shaft Speed Increase 5.7 rps to 7.5 rps	No Influence	Max T & Q indices decrease moderately	Moderate Increase	Moderate Increase a little less than ducted
Ice Thickness Increase 50 mm to 100 mm	Increase 100 % Plus	Increase 500 - 1000 %	Increase T up to 300 % Q up to 400 %	Increase HP up to 400 % LP up to 300 %
Block Size or Cut Width Increase 200 mm to 400 mm	Increase 50 % Plus	Increase 50 - 100 %	Increase T up to 300 % Q up to 100 %	Increase Up to 50 %
Large Very Thick Blocks up to 200 mm thick	Not Tested	Increase 100 - 200 mm thick 200 - 300 % increase	Not Tested	Not Tested
Pitch Reduction HP - LP	Variable Increase at Bollard, Decrease at Forward Speed	Thin Ice - Increase Thick Ice - Decrease	Thin Ice - Increase Thick Ice - None	Increase Thin Ice - 150 % Thick Ice - 50 %
Speed Increase	Increase 50 % Plus	Variable Overall Influence Small	Increase T up to 400 % Q up to 80 %	Increase Thin Ice - 200 % Thick Ice - 100 %
Relative Magnitude of Load Indices for 400 Block, HP, Bolard 100 mm Thick	Qmax 0.6 Tmax 2.5 For 50 mm Thick Blocks Load Indices Similar	1.8 Average 10.0 Average		
Relative Magnitude of Load Indices for LP, 200 mm Blocks or Cut Width, 100 mm thick, 1 m/s	Qmax 1.05 Qmean 0.13 Tmax 3.7	1.8 0.38 11.5	2.0 0.38 11 For Thin Level Ice, Ducted Load Indices 50 % Higher Than Open	2.1 0.5 15